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Fatigue Life of Laser Cut Metals

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1.0 INTRODUCTION AND BACKGROUND

The continuing evolution of rotating machinery emphasizes the need for multiplane-multispeed balancing. The manufacturing community is now recognizing the high-speed balancing technology developed by NASA-Lewis Research Center which has shown that the exceedingly flexible, high-speed shafts employed in new-generation machines do not respond adequately to balancing procedures commonly used in the past. Operating above one or more critical speds, these advanced shafts require a sophisticated approach to balancing if increased reliability is to be achieved. This requirement impacts the entire machine design in that multiplane access to the shafts may be necessary for an acceptable balance.

The ultimate success of any balancing procedure depends on the ability to apply balance corrections precisely and in optimum balance planes. The use of laser machining to apply these balance corrections holds promise for two problems: accessibility to balance planes in assembled machines, and reliance on labor-intensive balance corrections such as hand grinding and bolt-on weights. The program discussed in this report is an excellent step toward defining a practical method of accomplishing the desired degree of balancing accuracy by means of laser material removal.

Several important advantages exist to using a laser for material removal in rotor balancing. The most important of these advantages is that the material can be removed in an extremely accurate manner while the machine is operating, thus eliminating the necessity of stopping the rotor to add or remove material after each balancing run. A large amount of time may be saved, especially when working with high-inertia rotors. Another advantage to using a laser is that many machines can be balanced inside their normal housing without disassembly. Rotors can be accurately balanced on their production supports under actual dynamic conditions. Ports designed into the balancing planes of the machine housing can support lenses or adjustable focus lens tubes. These lenses would then be in position to converge the laser beam on the surface from which the material is to be removed. Using this method, rotors could be balanced to a much finer degree than they could be from outside the machine, thus resulting in a reduction of the dynamic loads and, in turn, a relaxation in the design constraints needed to withstand these loads. The potential impact on cost would be experienced both in a reduction in per unit balancing time and in reduced manufacturing costs.

Developments in multiplane flexible rotor and laser balancing technology under contract NAS3-14420 indicated that influence coefficient balancing methodology has considerable promise as a practical, cost-effective procedure for gas turbine manufacture and overhaul, especially when combined with laser machining for precise metal removal. MTI has demonstrated this approach in its laser balancing laboratory and in the commercial sector.

Further advances in laser balancing technology were subsequently made under contract NAS3-18520, which investigated flexible rotor balancing using a laser. A rotor was redesigned to accept balancing corrections, using a laser metal removal method. Then a laser and optical system were assembled to demonstrate this process. The laser capabilities as to the amount of material removed for variations in rotor speed, pulses, energy level, and type of lens were determined. The rotor was balanced through the first bending critical speed using the laser material removal procedure.

Also, as part of this NASA-administered Army-funded program, an investigation into laser material removal showed that laser burns act in a manner typical of mechanical stress raisers causing a reduction in fatigue strength; the fatigue strength is lowered relative to the smooth specimen fatigue strength. Laser-burn zones were studied for four materials: alloy steel 4340, stainless steel 17-4 PH, Inconel 718, and aluminum alloy 6061-T6. Calculations were made of stress concentration factors for laser-burn grooves of each material type. A comparison was then made to experimentally determine the fatigue strength reduction factor. In this work, however, no attempt was made to optimize the laser cut to maximize fatigue life, or to compare the effect of laser machining with the more conventional hand grinding method of material removal.

Both the United States Army and NASA recognized that to qualify laser machining for eventual use in balancing of gas turbine rotors, the actual reduction in fatigue life due to currently used hand grinding must be determined and compared with optimized results for a laser machining procedure. The program discussed in this report is an excellent step towards defining the relationship between the effects on fatigue life of conventional and advanced methods of material removal.

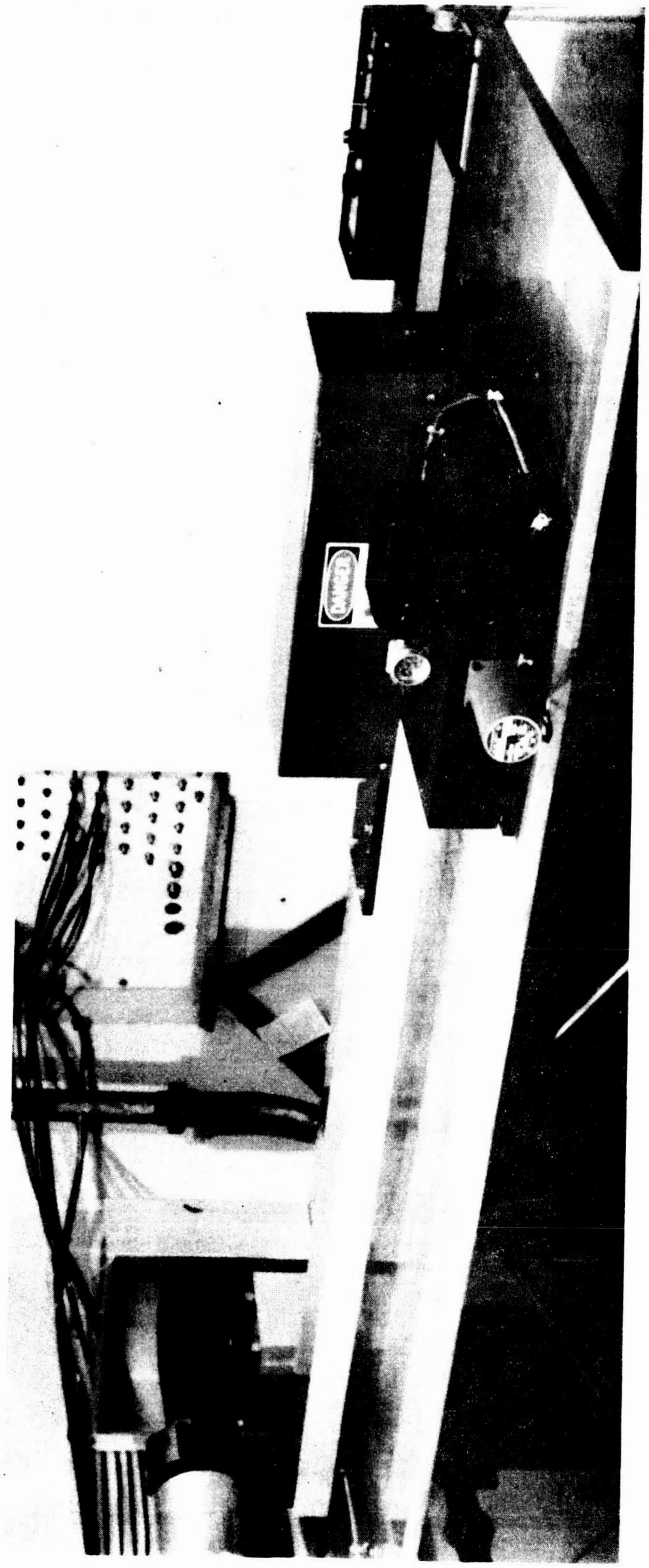

Figure 1

Specimen Test Fixture

2.0 DETAILS OF LASER SYSTEM, TEST SPECIMENS AND LASER MATERIAL REMOVAL

2.1 Laser System

The two lasers used for material removal were a model 11C Neodymium:glass laser from Coherent General and a Model SS531 Neodymium:YAG (Yttrium Aluminum Garnet) laser from Raytheon. Both lasers emit pulses at the same wavelength, the primary difference between the two being the high repetition rate and, therefore, high average power possible with the Neodymium:YAG laser.

Laser Specification

	Nd:glass	Nd:YAG
Lasing Wagelength	1.06 micrometers	1.06 micrometers
Energy Output	40 joules	44 joules
Max Repetition Rate	.5 pulses per second	200 pulses per second
Average Power	20 Watts	400 Watts

2.2 Test Fixture

The Nd:glass laser was mounted on an optical table illustrated in Figure 1. Also shown is a spindle and 3 jaw lathe chuck where the specimens were installed for laser firing. A variable speed motor provides a means of gradually increasing rotor speed. The stepping table on which the laser is mounted allowed the laser beam to be centered on the specimen and also provided the necessary burn zone width by stepping the laser a specified increment between laser shots. Focussing of the beam was accomplished by a movable 10 diopter lens.

The MTI control system used to control the laser is described in detail in Appendix A. It is an Intel microprocessor based system.

Work with the Nd:YAG laser was accomplished at the Raytheon application laboratory. The 3 jaw chuck and variable speed motor was mounted on a base plate which was installed on a stepping table that was positioned under the fixed beam output of the laser. The workpiece was, therefore, moved to provide the burn zone width rather than the laser moving as in the other setup.

2.3 Procedure for Laser Burns, Hand Grinding, and Machining Fatigue Specimens

The following procedures outline the method used to produce the three types of fatigue specimens. The sketches are included as Appendix B.

- Receive rough machine forgings
- Rough machine to sketch SK-7036
- Install laser burn zones or hand-ground zones in 10 equally spaced angular locations
- Saw into 10 pieces on radial line through center of the cylinder
- Final machine to sketch SK-7038
- Perform fatigue tests

2.3.1 Nd:glass Laser Test Specimens

Fatigue test specimens were prepared from forgings of the following four materials:

- alloy steel AISI 4340
- stainless steel 17-4 PH
- Inconel 718
- Aluminum alloy 6061-T6

Metallurgical reports for these materials are presented in Appendix C. The installation of the Nd:glass laser burn zones is summarized below. All laser shots are fired at a pulse duration of .9 msec and a target speed of 1500 rpm.

Material	Shots/Pass	Stepsize	Total Shots	Weight Removed
4340	125	.008 in.	726	1.45 gm
17-4 PH	125	.008 in.	726	1.84 gm
Inconel 718	140	.008 in	410	1.9 gm
Al 6061-T6	60	.012 in.	320	.80 gm

2.3.2 Nd:YAG Laser Test Specimens

The installation of the Nd:YAG laser burns are summarized below:

	MATERIAL			
	17-4	4340	Inconel	Aluminum
Pulse Duration	.9 msec	.9	.9	.9
Speed	1500 rpm	1500	1500	1500
Stepper Speed	10 in/min	7	7	10
Laser Input Power	11.5 kW	11.5	11.5	11.5
Repetition Rate	10 shots/sec	10	10	10
Shots Fired	455	650	650	455
Total Removed	1.5 gm	1.24	2.29	.56
Removal/Shot	3.3 mg/shot	1.9	3.5	1.2

2.3.3 Hand-Ground Specimens

The hand-ground specimens were prepared for each material after the preparation of the laser specimens. Depth measurements could therefore be taken for the laser parameters selected and the macroscopic geometry of the burn zone duplicated by hand grinding. All hand ground material removal was accomplished in a manner representative of Army overhaul procedures for component balancing.

3.0 EXPERIMENTAL PROCEDURE

Fatigue tests were conducted for each of the three types of material removal discussed in Section 2.0, two of which were laser induced and one that was caused by grinding. All fatigue testing was performed with cyclic loading applied as four-point bending. Testing was performed in an MTS closed-loop electrohydraulic test system with a maximum load capacity of 20,000 lbs. The load profile was sinusoidal with a minimum load (P_{min}) to maximum load (P_{max}) ratio (P_{min}/P_{max}) of 0.05. Figure 2 shows the MTS fatigue test machine with a specimen installed.

In the four point bending configuration, the load required for a given bending stress was calculated using the following equation.

$$P = \frac{2\ I\ S_{max}}{lc}$$

where

P = Applied load

S_{max} = Maximum outer fiber bending stress

c = Distance from neutral axis to outer fiber

l = Moment arm (2" for this setup)

I = Moment of inertia for test region cross section.

This equation is the flexure formula solved for applied load. Each test was conducted at an R ratio (ratio of minimum stress to maximum stress) of 0.05; therefore, the controlled stress range, ΔS, was 0.95 times S_{max}. The waveform was sinusoidal. Each individual test was conducted at a constant frequency of cycling. However, the frequency varied from 10 Hz to 25 Hz depending on the magnitude of the applied load and the resulting specimen deflection. At high loads and large deflections, the lower test frequencies were used to stay within the performance capabilities of the test machine. Since all tests were conducted in air at room temperature, no frequency effect would be expected. For these materials and test conditions, a frequency greater than about 170 Hz

Figure 2

MTS Fatigue Machine

would have to be exceeded before a frequency effect would be expected. (See ASTM standard E466, Section 7.4.)

The fatigue data from both the ground specimens and the laser-burned specimens are presented in Tables 1 to 8 for each of the four materials investigated. These data are plotted as S_{max} versus cycles to failure, N, in figures 3 through 6. Each figure contains all fatigue data for a particular material. The upper S-N curve (circular symbols) is the hand-ground specimen baseline data, and the lower S-N curves (triangular and inverted triangular symbols are the laser-burned specimen data.

The S-N curves in the figures were obtained by least squares fitting the data to the linear relationship,

$$LOG(N) = A + B\ LOG(S_{max})$$

where A and B are the intercept and slope, respectively. No runout data were included during the linear regression analysis. However, the data were taken into account when it was obvious that the complete S-N curve was more appropriately described by two straight lines where one line is horizontal at the fatigue limit.

The object of this test program was to evaluate the effects of two methods of laser material removal (one performed by the MTI laser and the other performed by the Raytheon laser). The S-N curves for these two methods of laser material removal are compared to that for the specimens having material removed by grinding.

Additional insight into the fatigue property degradation caused by laser burning is provided by photo micrographs of sections through the laser affected region near the surface. The series of photo micrographs in Figures 7 through 18 show representative microstructural features associated with laser burning for the MTI laser specimens and the hand-ground specimens for Aluminum and 4340.

4.0 RESULTS AND DISCUSSIONS

A reduction in fatigue strength caused by the laser burn is not unexpected as any mechanical stress raiser, such as a keyway will lower the fatigue strength relative to the smooth specimen fatigue strength. The typical surface quality achieved for the laser burns was approximately 500-750 rms whereas the ground removal surface quality was on the order of 64 rms with well radiused edges. With the Nd:glass laser, the MTI control system was used to control various laser parameters to minimize the fatigue strength degradation. For instance, for repeated passes across the laser burn, the pass width was decreased to taper the edges and additional shots fired to clean slag out of the burn zone. The Nd:YAG laser specimens were fired at maximum average power of the laser and all parameters established to achieve a maximum material removal rate.

Contrary to initial expectations, the high energy Nd:YAG laser provided laser burns that reduced the fatigue strength to a lesser extent than the Nd:glass laser burns. One factor contributing to the higher fatigue strength of the Nd:YAG laser specimens is the difference in pulse energy versus time of the two types of lasers. Both laser types have similar energy rise times from 0 joules to full pulse energy, but the Nd:YAG laser pulse is relatively constant energy throughout the pulse duration while the glass laser has a spiked profile that starts to decrease in energy earlier in the pulse duration. This difference resulted in a more even depth of laser cut circumferentially for the Nd:YAG laser specimens.

Another factor in the higher fatigue strength of the Nd:YAG laser specimen is the difference in motion control. The Nd:YAG laser was fired at ten shots per second while the workpiece was moving under the beam. When a pass across the burn zone width was repeated, the shots fired were not precisely on top of shots from the previous pass therefore producing less pronounced ridges across the burn zone. The lower repetition rate Nd:glass laser was fired with no relative axial motion between the laser and the workpiece during firing. Stepping was accomplished in the time between laser shots.

The fatigue life degradation illustrated in Figures 3 - 6 is summarized in the table below. Note that the degradation in fatigue life is much less at 10^5 cycles to failure than at 10^7 cycles to failure.

Reduction in Fatigue Strength for Laser-Fired Specimens versus Hand-Ground

	%Reduction @ 10^5 cycles		%Reduction @ 10^7 cycles	
Materials	Nd:glass	Nd:YAG	Nd:glass	Nd:YAG
4340	23%	8.7%	64%	57%
17-4 PH	29%	12%	62%	58%
Inconel 718	23%	11%	34%	37%
AL 6061-T6	28%	8%	47.6%	37%

5.0 CONCLUSIONS

The goal of the physical appearance of the laser burn zone is to duplicate the appearance of the machine or hand grinding technique by the overhaul center balance machine operator. Typical specifications for hand grinding have a zone defined on a blueprint and limited by a not to exceed depth. The ability of the operator to remove the required amount of material is dependent primarily on operator experience.

The method of producing a distributed laser removal zone of a size representative of a turbine balance correction is undergoing continuing development. The low removal rate possible with Nd:glass lasers limits the size of correction weights that can be achieved in a reasonable period of time. Development of the high powered Nd:YAG lasers has provided the capabilities required to remove enough material to balance gas turbine engines in an efficient process. In ongoing work at MTI, removal rates of 2 grams per minute have been demonstrated on turbine hardware. Advances in control of the high repitition rate laser have also provided balance corrections with a better than 250 rms surface finish, significantly smoother than the laser burns studied under this contract.

Use of a laser for material removal to balance turbine components has been demonstrated. Although the fatigue strength is reduced from that of a hand-ground removal, it is likely that in most balancing applications the removal from a low-stressed sacrificial area would not present a problem in terms of life of the component. In addition, further advances in laser control are already producing burn zones that have a much improved surface quality. Based on the two to three fold improvement in surface smoothness achieved since these tests were conducted and the reduced fatigue life degradations experienced with the Nd:YAG laser, the further development of laser balancing of turbine components is warranted.

Table 1

FATIGUE DATA FOR 17-4 PH SPECIMENS WITH MATERIAL REMOVED BY GRINDING

Specimen No.	Stress (psi)	Cycles to Failure
G1	62,220	$>10^7$
G2	84,374	692,440
G3	80,521	$>10^7$
G4	87,140	$>10^7$
G5	91,381	267,360
G6	89,042	175,410
G7	84,420	799,270
G8	79,690	$>10^7$
G9	83,952	551,490

Table 2

FATIGUE DATA FOR 17-4 PH SPECIMENS WITH MATERIAL REMOVED BY A LASER

SPECIMENS WITH MATERIAL REMOVED BY MTI LASER

Specimen No.	Stress (psi)	Cycle to Failure
L1	42,609	557,040
L2	34,608	864,830
L3	24,909	$>10^7$
L4	49,100	232,890
L5	29,409	1,281,000
L6	41,007	669,640
L7	31,312	1,271,000

SPECIMENS WITH MATERIAL REMOVED BY RAYTHEON LASER

L1B	62,878	264,000
L2B	72,126	164,300
-		
-		
LB5	34,493	2,152,700
L6B	25,586	$>10^7$
L7B	45,246	1,023,360
L85	36,279	2,207,660

Table 3

FATIGUE DATA FOR 6061 ALUMINUM SPECIMENS WITH MATERIAL REMOVED BY GRINDING

Specimen No.	Stress (psi)	Cycle to Failure
G1	15,109	3,879,530
G2	9,863	$>10^7$
G3	17,873	2,606,540
G4	26,856	58,650
G5	12,481	$>10^7$
G6	14,208	$>10^7$
G7	22,342	571,990
G8	13,253	$>10^7$

Table 4

FATIGUE DATA FOR 6061 ALUMINUM SPECIMENS WITH MATERIAL REMOVED BY LASER

SPECIMENS WITH MATERIAL REMOVED BY MTI LASER

Specimen No.	Stress (psi)	Cycles to Failure
L1	15,000	1,112,480
L2	14,137	886,940
L3	13,068	886,200
L4	11,155	1,948,530
L5	10,052	3,769,850
L6	8,950	3,426,130
L7	8,063	4,171,920
L8	6,402	4,683,510

SPECIMENS WITH MATERIAL REMOVED BY RAYTHEON LASER

L1B	17,822	550,800
L2B	11,123	3,998,220
L3B	21,449	157,570
L4B	29,293	82,970
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L7B	15,537	833,280
L8B	12,815	2,385,590

Table 5

FATIGUE DATA FOR 4340 STEEL SPECIMENS WITH MATERIAL REMOVED BY GRINDING

Specimen No.	Stress (psi)	Cycles to Failure
G2	91,295	344,680
G3	82,055	$>10^7$
G4	87,274	536,420
G5	86,405	290,570
G6	82,938	$>10^7$
G7	85,109	318,160
G8	80,768	199,330
G9	82,566	189,200

Table 6

FATIGUE DATA FOR 4340 STEEL SPECIMENS WITH MATERIAL REMOVED BY A LASER

SPECIMENS WITH MATERIAL REMOVED BY MTI LASER

Specimen No.	Stress (psi)	Cycles to Failure
L2	83,267	59,570
L3	73,723	46,360
14	65,388	94,920
L5	46,705	356,400
L6	36,984	807,530
L7	33,124	1,481,070
L8	78,517	84,470
L9	45,271	$>10^7$

SPECIMENS WITH MATERIAL REMOVED BY RAYTHEON LASER

Specimen No.	Stress (psi)	Cycles to Failure
L1B	57,572	228,000
L2B	53,376	620,420
L3B	49,295	760,650
L4B	44,769	1,087,750
L5B	63,789	261,540
L6B	35,663	$>10^7$
L7B	90,187	95,340

Table 7

FATIGUE DATA FOR INCONEL 718 SPECIMENS WITH MATERIAL REMOVED BY GRINDING

Specimen No.	Stress (psi)	Cycles to Failure
G1	54,688	3,563,830
G2	63,455	827,940
G3	59,460	1,453,080
G4	80241	322,150
G5	45,425	>10^7
G6	79,497	601,800
G7	71,723	616,800
G9	54,148	1,228,170

Table 8

FATIGUE DATA FOR INCONEL 718 SPECIMENS WITH MATERIAL REMOVED BY A LASER

SPECIMENS WITH MATERIAL REMOVED BY MTI LASER

Specimen No.	Stress (psi)	Cycles to Failure
L1	44,816	1,119,610
L2	63,035	223,620
L3	44,752	1,771,650
L4	53,768	566,250
L5	68,644	152,560
L6	81,300	108,200
L7	85,298	169,210
L8	36,928	3,430,150

SPECIMENS WITH MATERIAL REMOVED BY RAYTHEON LASER

L2B	35,921	2,795,590
L4B	45,063	1,025,460
L5B	78,983	231,690
L6B	54,573	473,220
L7B	62,983	327,460
L8B	86,408	133,570

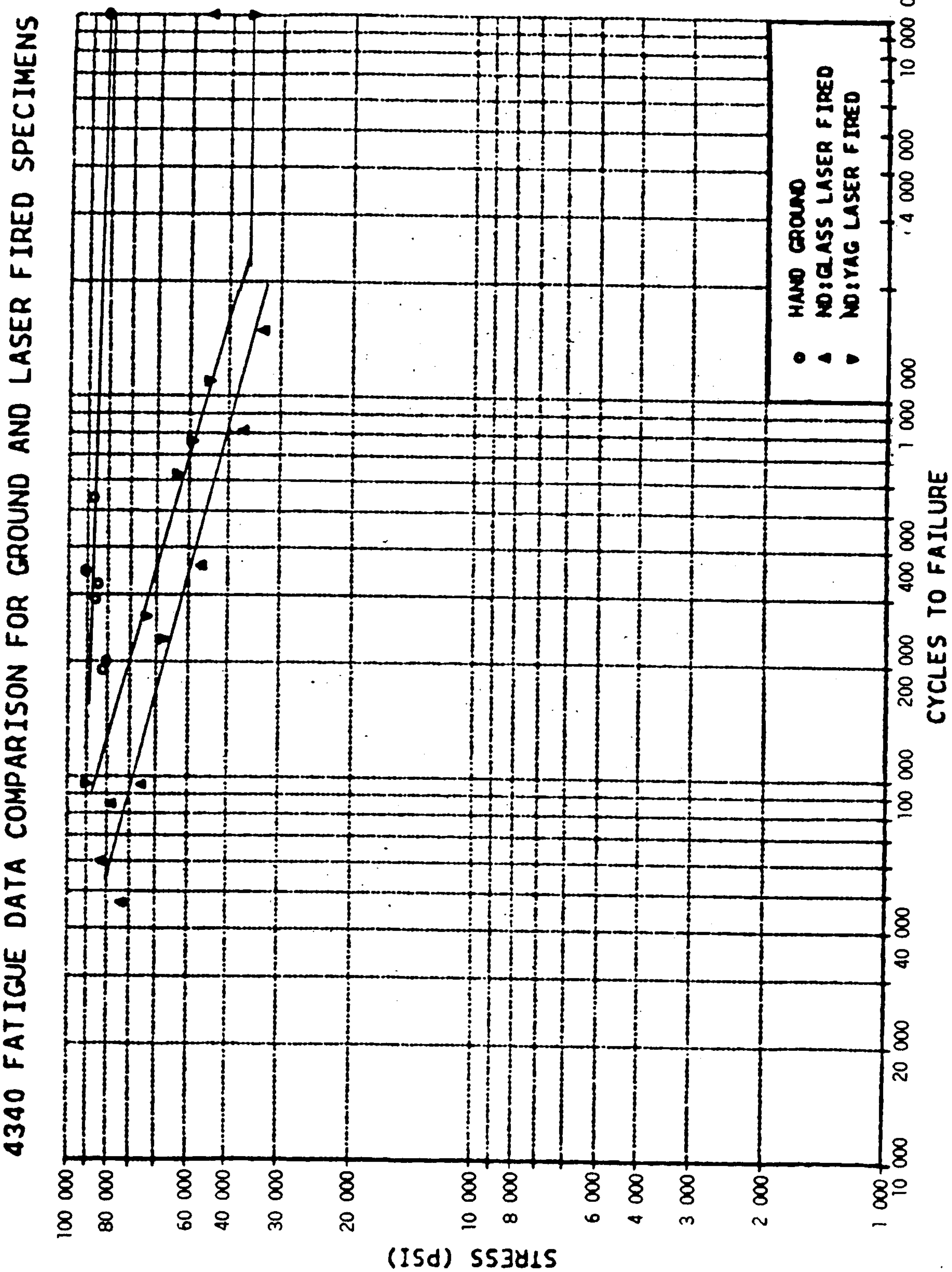

4340 FATIGUE DATA COMPARISON FOR GROUND AND LASER FIRED SPECIMENS
HAND GROUND
ND:GLASS LASER FIRED
ND:YAG LASER FIRED
STRESS (PSI)
100 000
80 000
60 000
40 000
30 000
20 000
10 000
8 000
6 000
4 000
3 000
2 000
1 000
CYCLES TO FAILURE
10 000
20 000
40 000
100 000
200 000
400 000
1 000 000
4 000 000
10 000 000

Figure 3

17-4PH FATIGUE DATA COMPARISON FOR GROUND AND LASER FIRED SPECIMENS

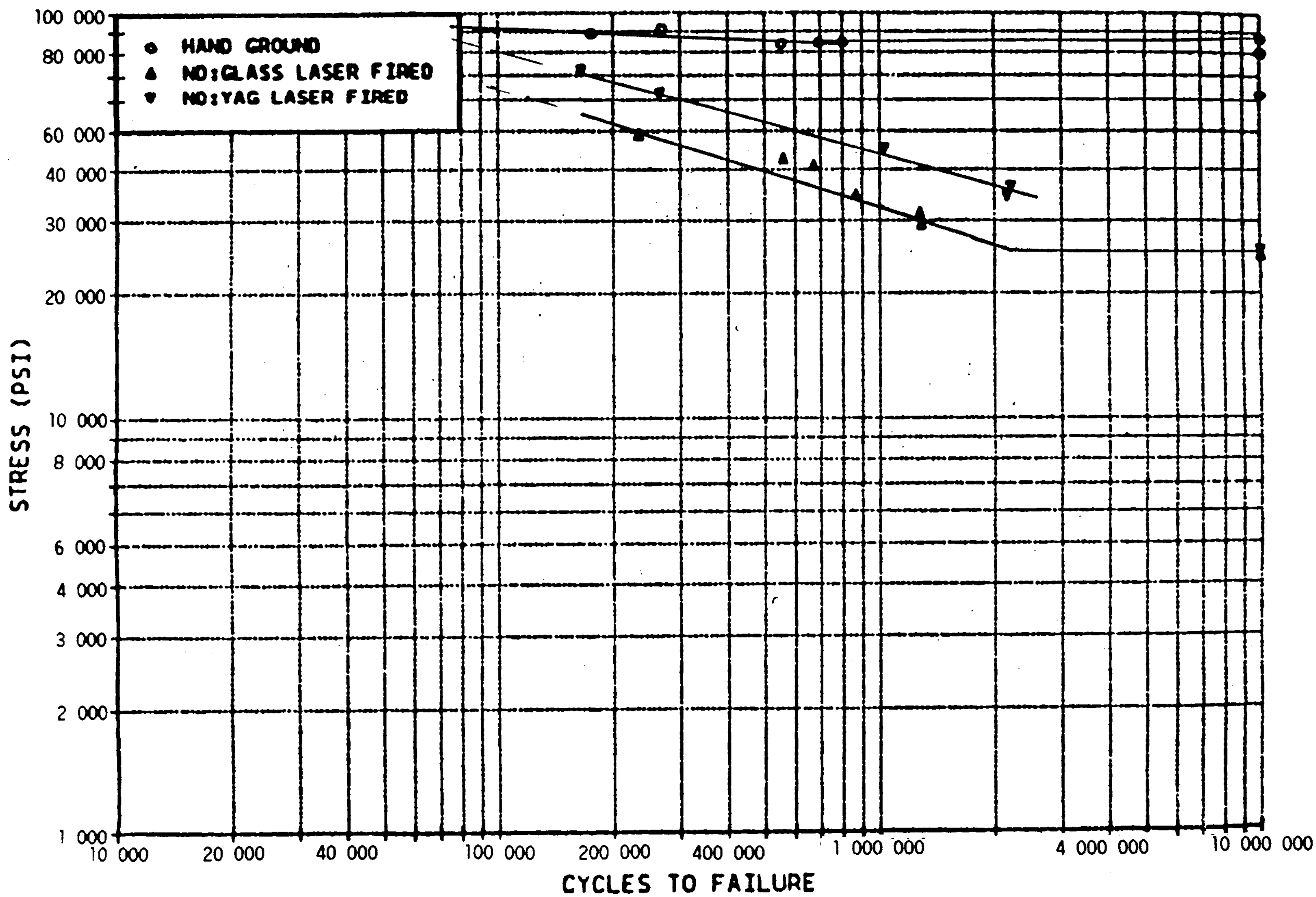


Figure 4

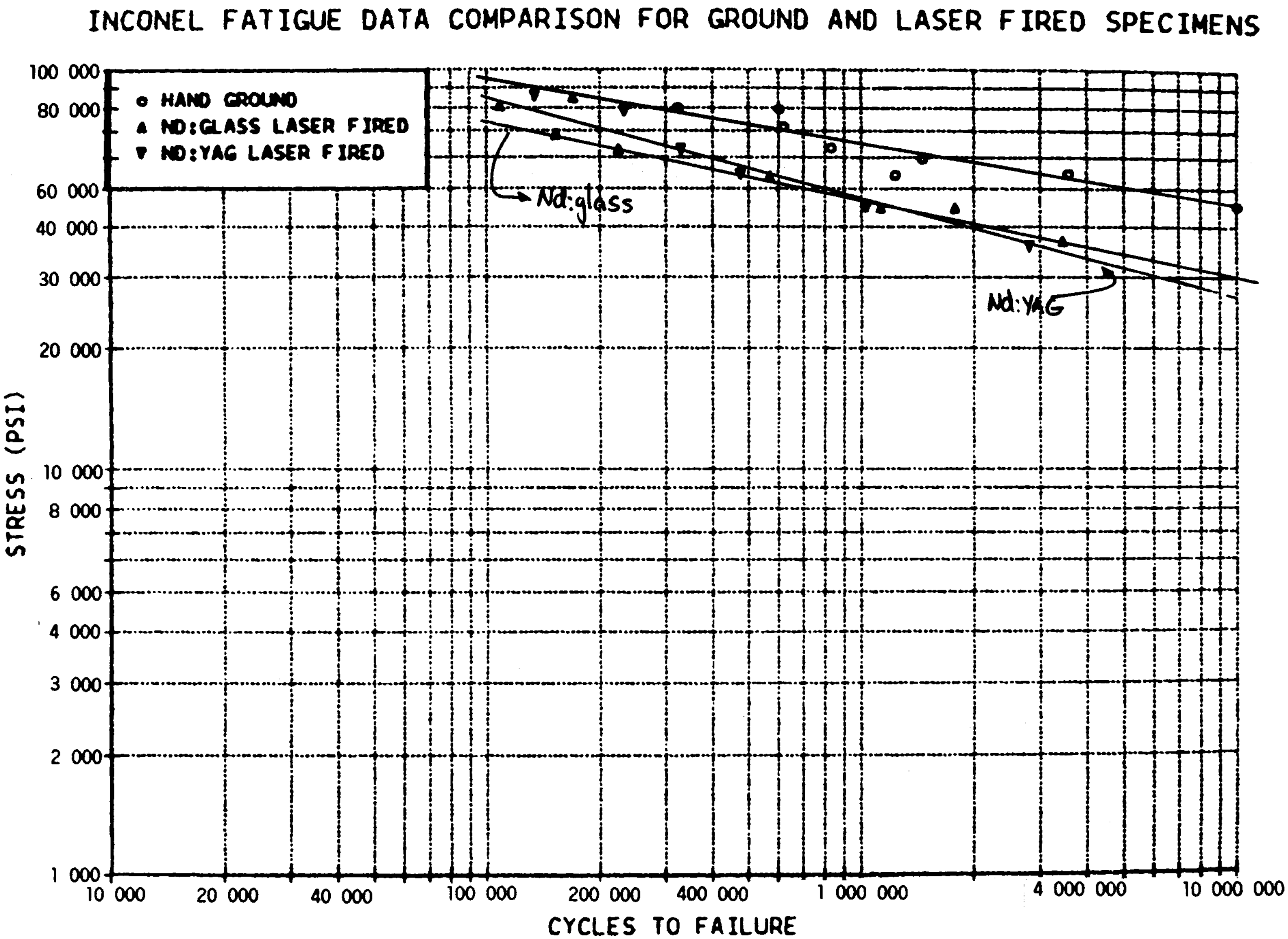

INCONEL FATIGUE DATA COMPARISON FOR GROUND AND LASER FIRED SPECIMENS
HAND GROUND
ND:GLASS LASER FIRED
ND:YAG LASER FIRED
Nd:glass
Nd:YAG
STRESS (PSI)
100 000
80 000
60 000
40 000
30 000
20 000
10 000
8 000
6 000
4 000
3 000
2 000
1 000
CYCLES TO FAILURE
10 000
20 000
40 000
100 000
200 000
400 000
1 000 000
4 000 000
10 000 000

Figure 5

ALUMINUM FATIGUE DATA COMPARISON FOR GROUND AND LASER FIRED SPECIMENS

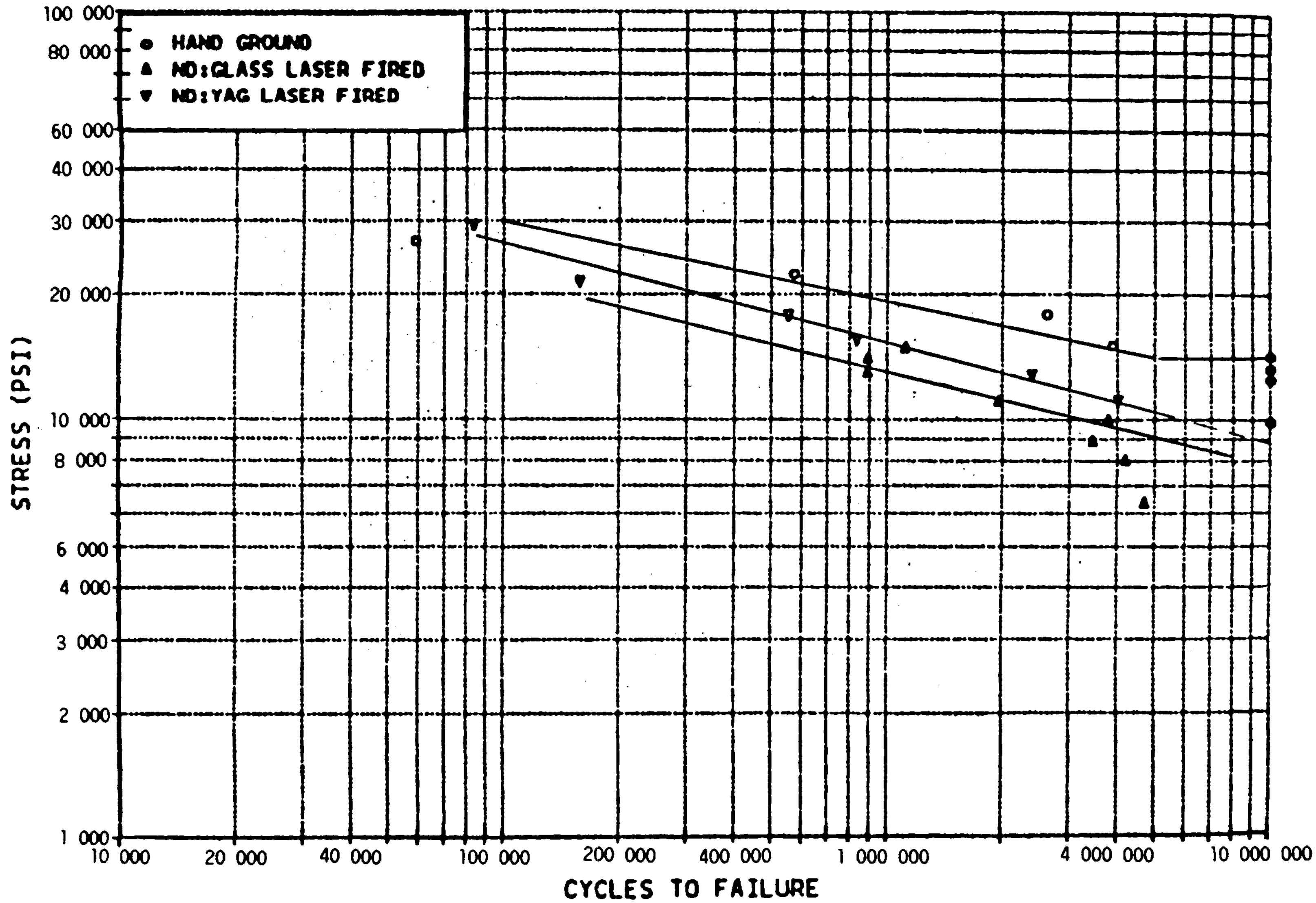
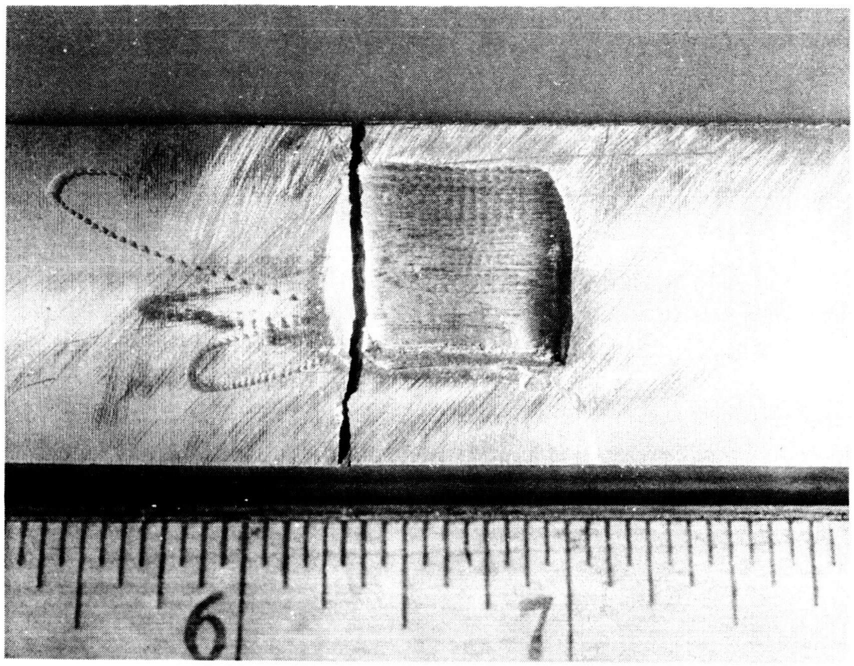
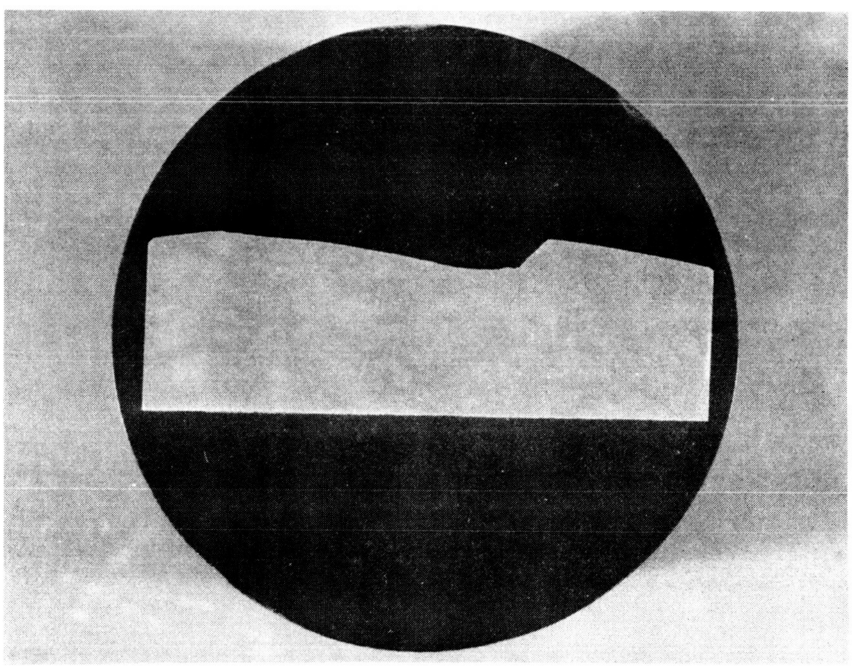


Figure 6



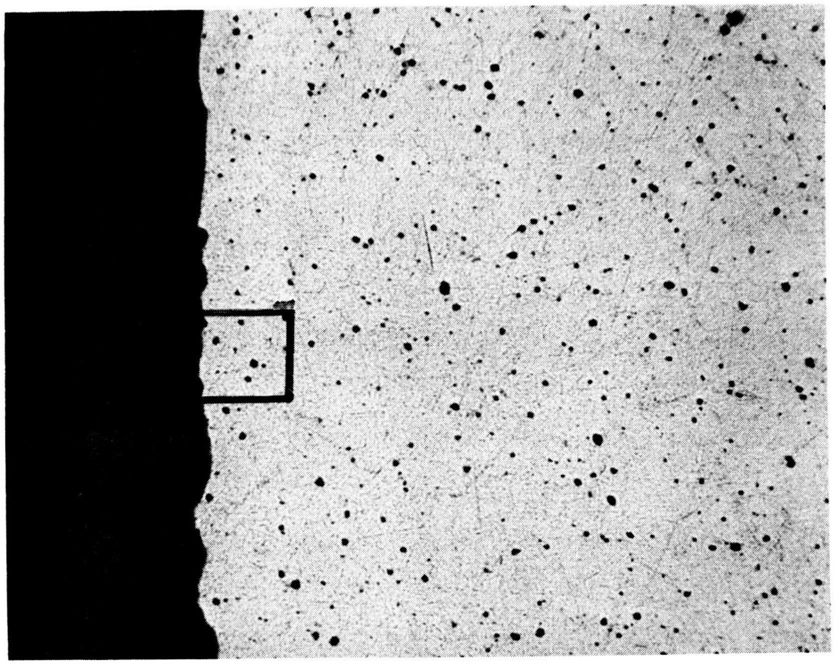
L6322 x1.7

FIGURE 7a: Fatigue specimen G-1 with hand ground notch. 6061-T6 Aluminum.



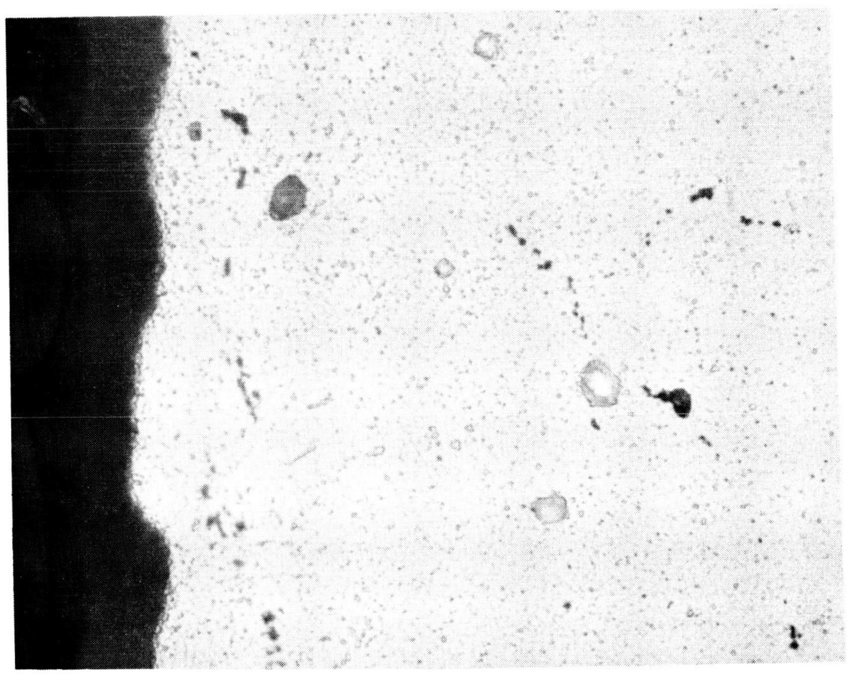
L6368 x2.6

FIGURE 7 b: Mounted cross-section of above specimen showing profile of hand ground notch.



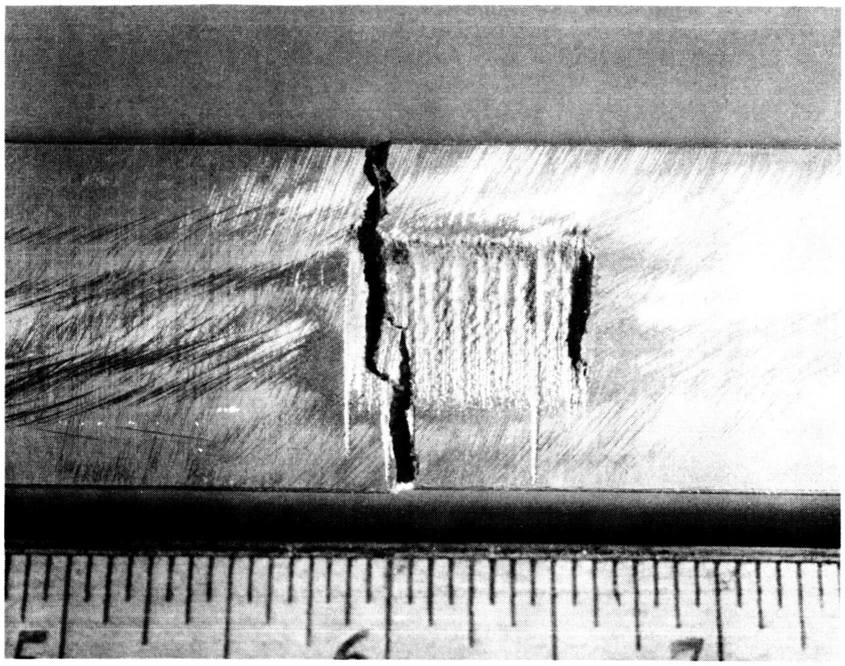
L6373 x125

FIGURE 8a: Light microscope photograph of microstructure of specimen G-1 below ground area. 6061 T-6 Aluminum



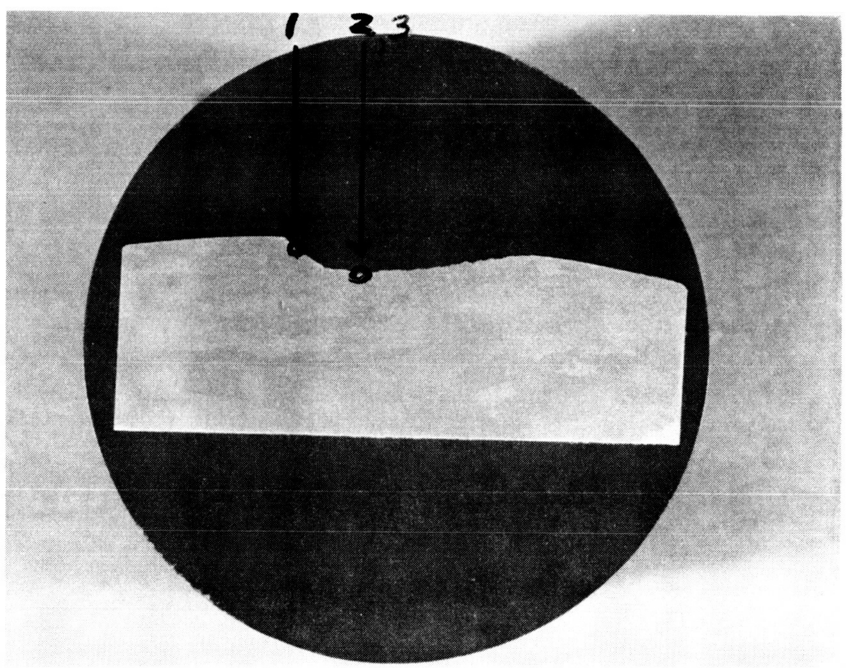
L6372 x1000

FIGURE 8b: Higher magnification of microstructure from inset shown above.



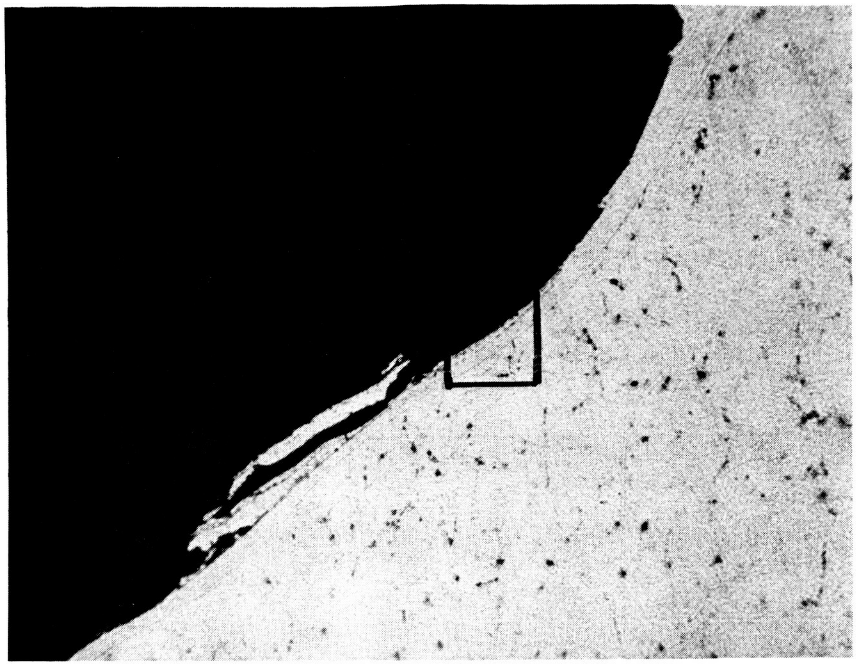
L6321 x1.7

FIGURE 9a: Fatigue specimen L-2 with laser burn.
6061-T6 Aluminum



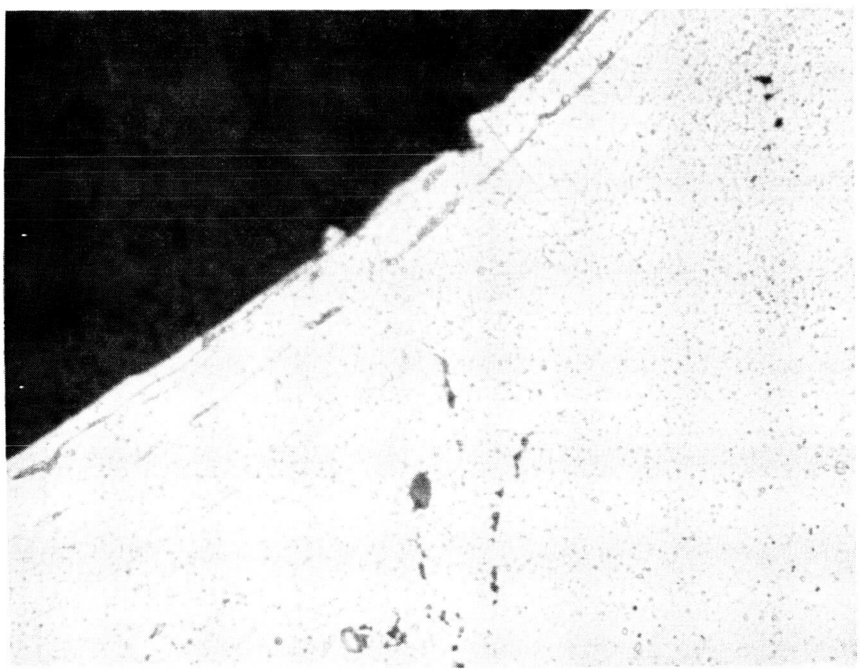
L6367 x2.6

FIGURE 9b: Mounted cross-section of above specimen showing profile of laser burn (MTI laser).



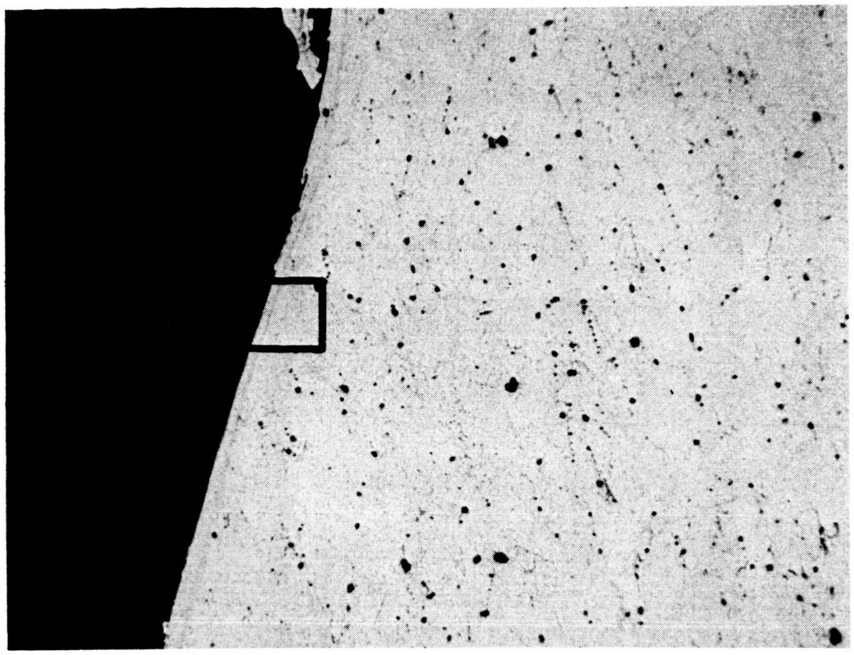
L6363 x125

FIGURE 10a: Light microscope photograph of microstructure of specimen L-2, area 1, near leading edge of laser burn.



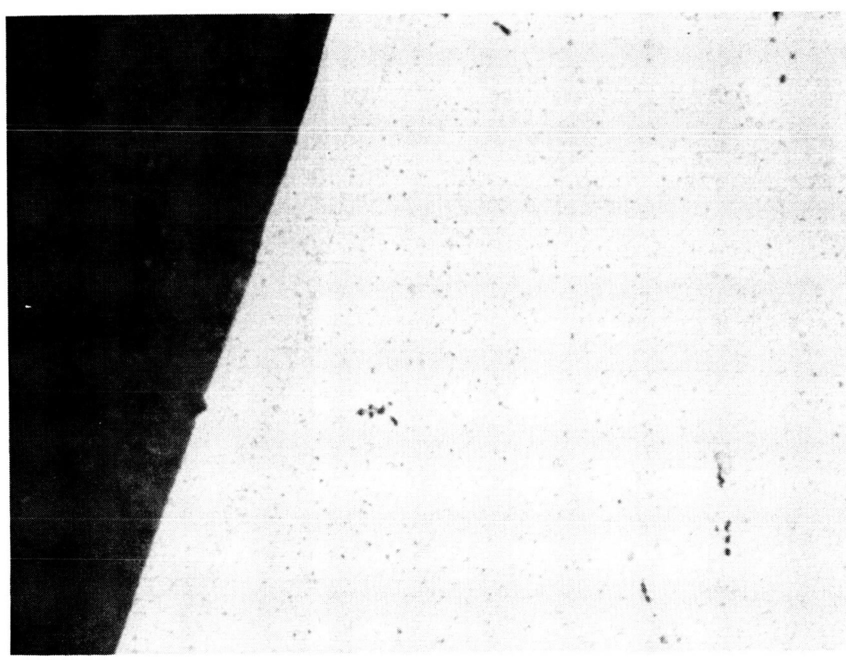
L6364 x1000

FIGURE 10b: Higher magnification of microstructure from inset shown above.



L6374 x125

FIGURE 11a: Light microscope photograph of microstructure of specimen L-2, area 2.

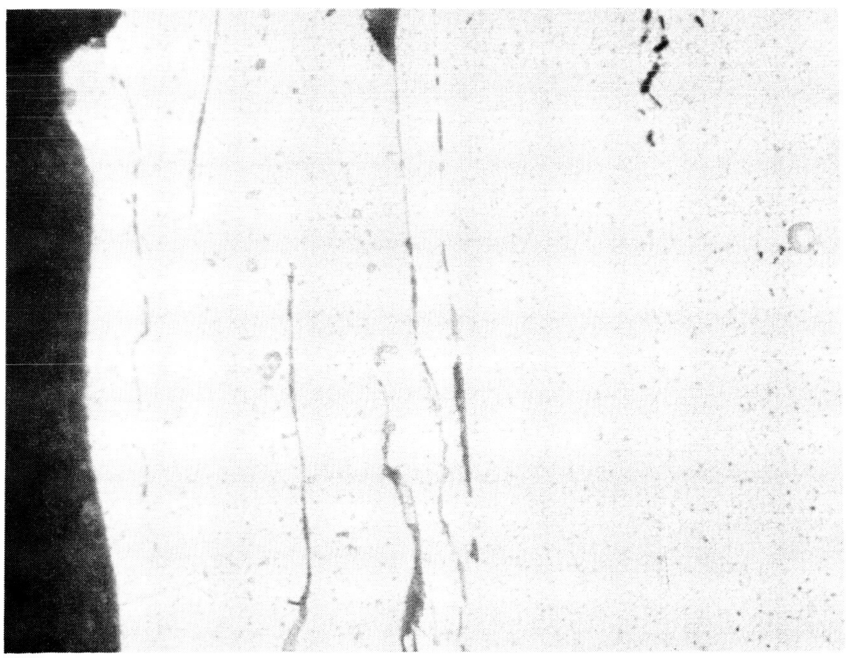


L6377 x1000

FIGURE 11b: Higher magnification of microstructure from inset above.

L6375 x125

FIGURE 12a: Light microscope photograph of microstructure of specimen L-2, area 3, of laser burn



L6376 x1000

FIGURE 12b: Higher magnification of microstructure from inset shown above.

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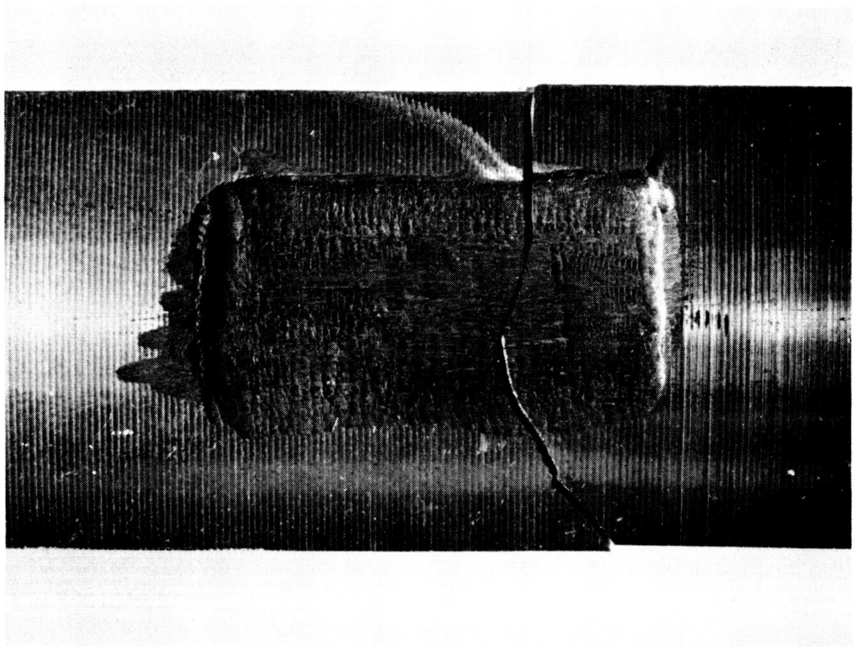
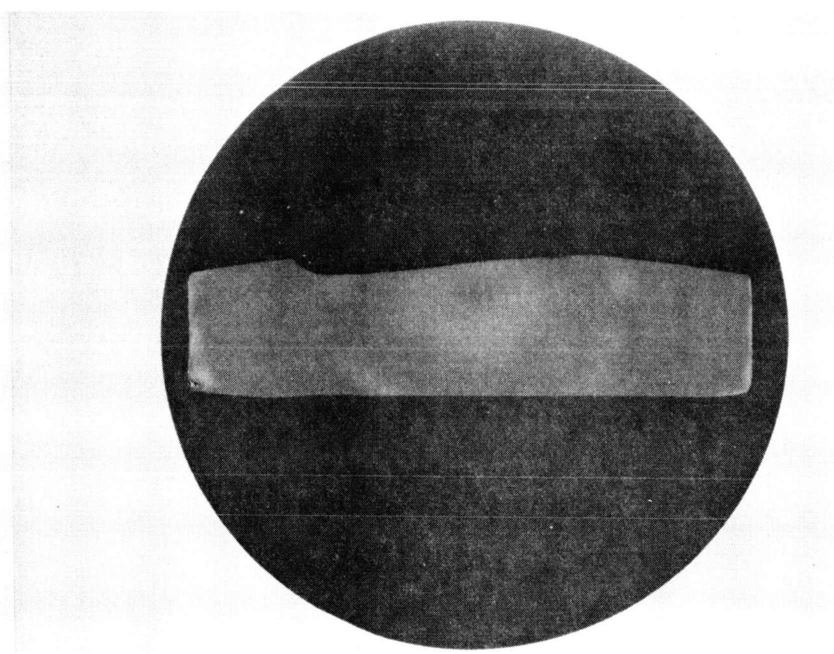


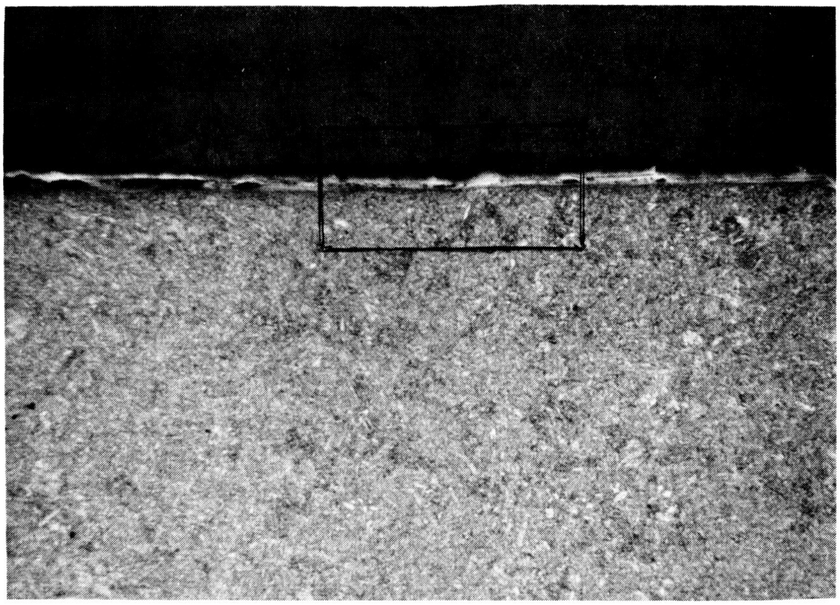
L6512 x2

FIGURE 14a: Fatigue specimen G2 (4340 steel) with hand ground notch.



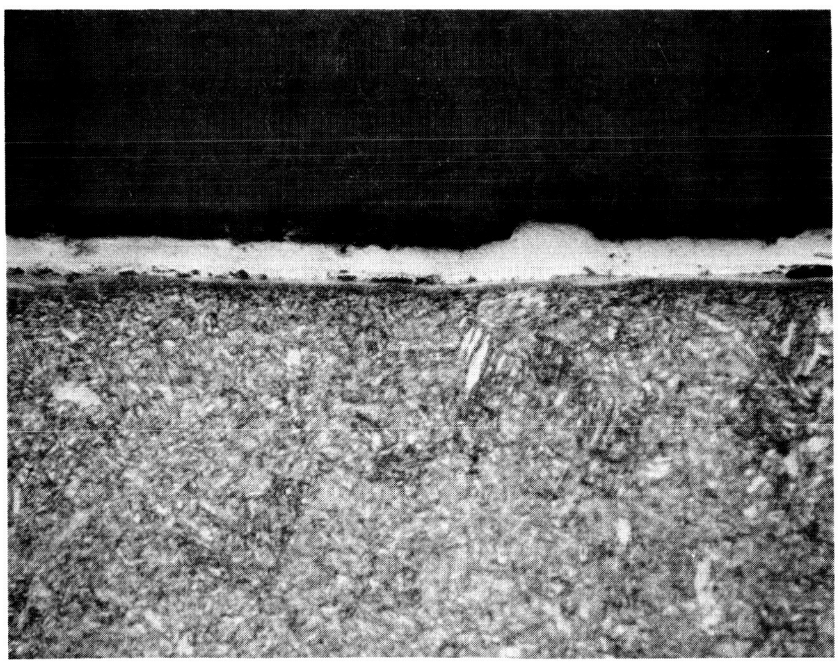
L6590 x2.6

FIGURE 13: Mounted cross-section of above specimens showing profile of hand ground notch.



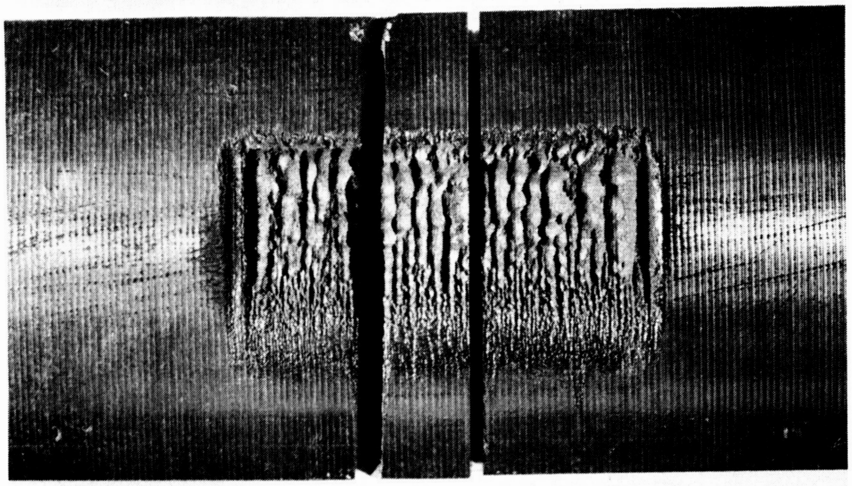
L6587 x125

FIGURE 15a: Optical photomicrograph of microstructure of specimen G2 (4340 steel) in ground area.



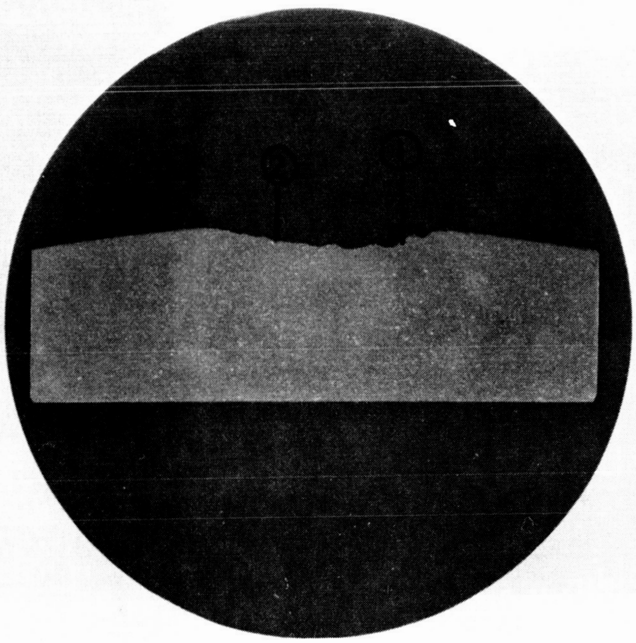
L6588 x400

FIGURE 14: Higher magnification photomicrograph of microstructure from inset shown above.



L6511 x2

FIGURE 13a: Fatigue specimen L2 (4340 steel) with laser burn.

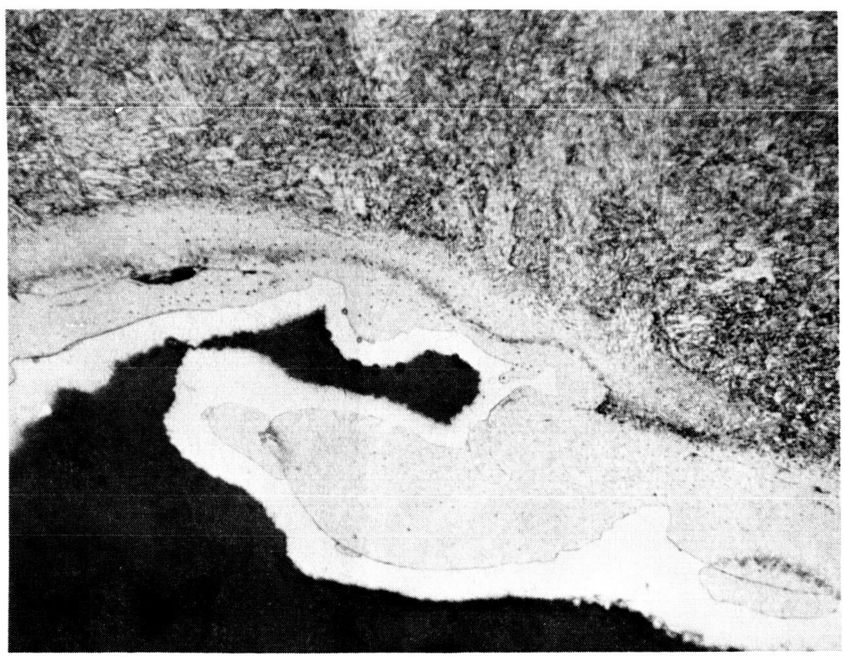


L6589 x2.6

FIGURE 15: Mounted cross-section of above specimen shown.

L6581 x125

FIGURE 16a: Optical photomicrograph of the laser burn in specimen L2 (4340 steel). Area 1.



L6582 x400

FIGURE 16b: Higher magnification optical photomicrograph of microstructure from inset shown above.

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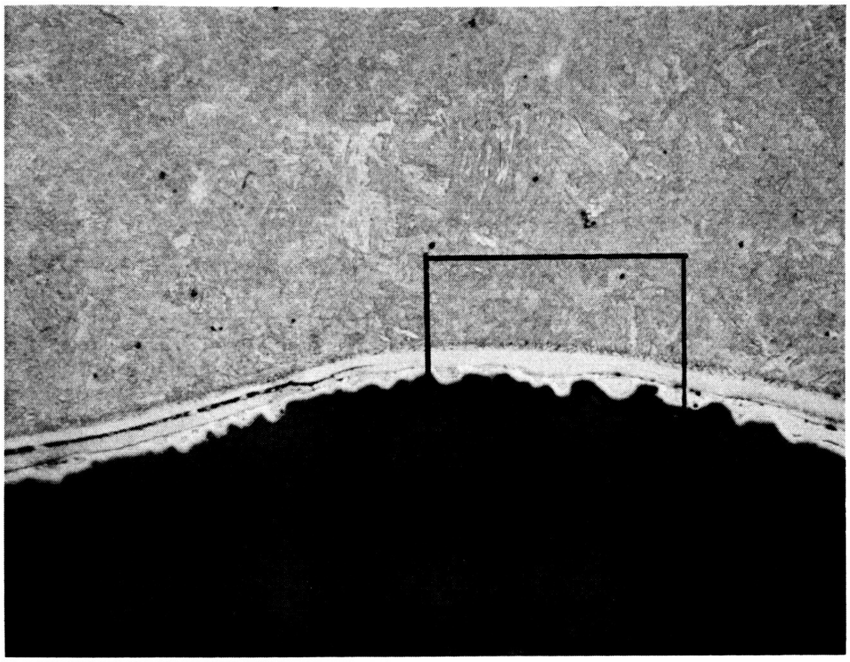
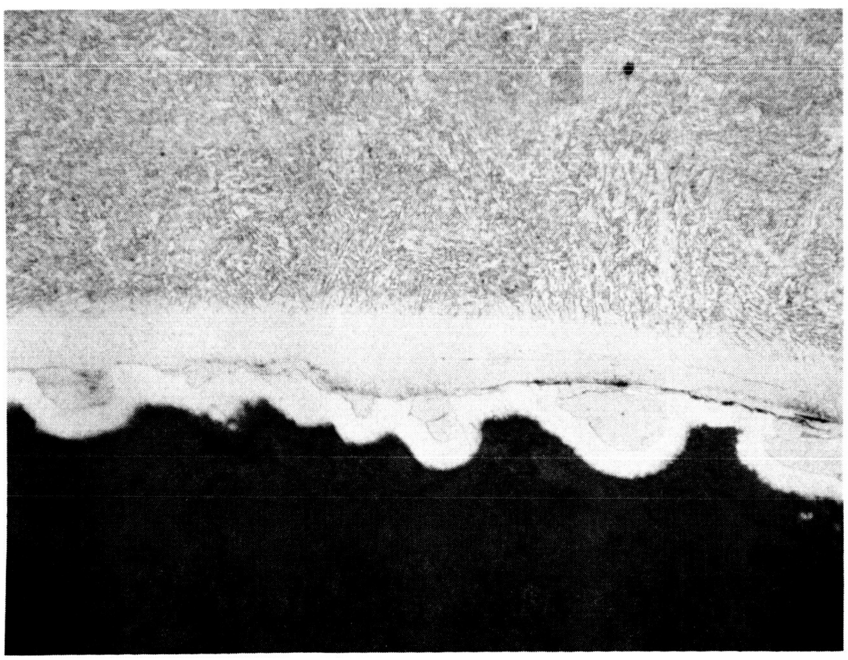
OF POOR QUALITY



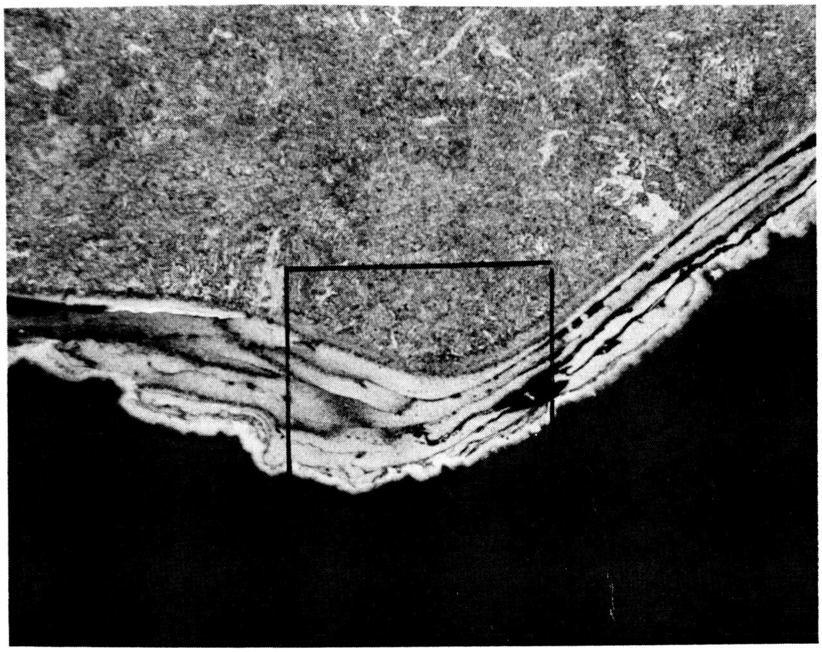
L6585 x125

FIGURE 17a: Optical photomicrograph of microstructure of specimen L2 (4340), in area 2.



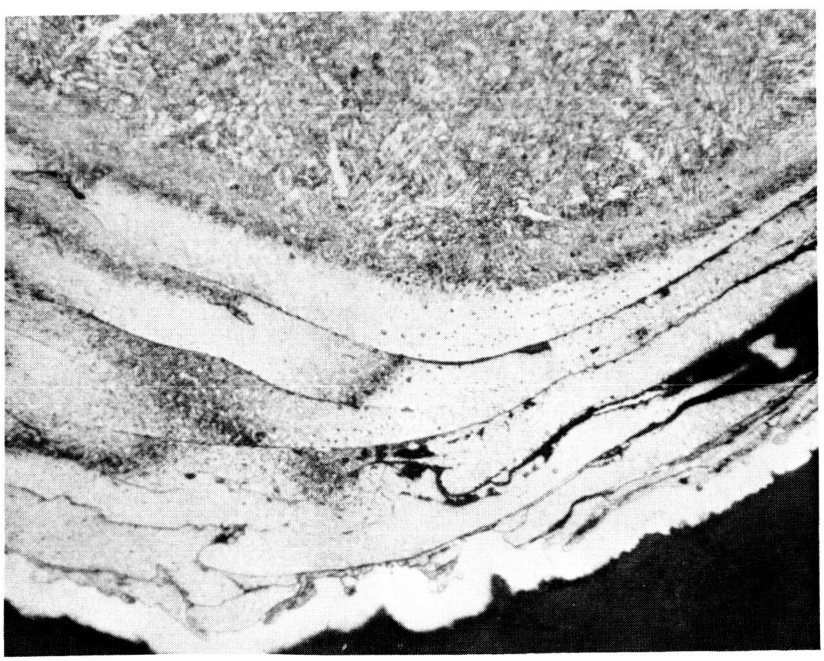
L6586 x400

FIGURE 17b: Higher magnification photomicrograph of area from inset shown above.



L6583 x125

FIGURE 18a: Photomicrograph of microstructure of specimen L2 (4340 steel), area 1, near the leading edge of the laser burn.



L6584 x400

FIGURE 18b: Higher magnification of microstructure from inset shown above.

APPENDIX A

MTI Laser Balancing System Description

DEVELOPMENT OF A MICROPROCESSOR-CONTROLLED LASER SYSTEM FOR AUTOMATED PRECISION BALANCING

W. Bessler M. Martin
Mechanical Technology Incorporated
Latham, NY

Abstract

This paper describes the development and capabilities of a fully automated, microprocessor-controlled laser system for the precision multiplane balancing of both rigid and flexible spinning rotors. The system computes all balance plane corrections simultaneously and then, under microprocessor supervision, uses a pulsed laser to precisely remove material as the part rotates. The operator and the user-friendly microprocessor software interact through a video screen and key pad. A closed-loop feedback logic that uses vibration sensors to automatically update laser commands is used to assure that residual imbalance is kept within operator-specified limits. Advantages of this approach over the conventional method of material removal (drilling or grinding) include increased precision and productivity and the elimination of rejected workpieces resulting from human error. The system is designed for retrofit to existing balance machines and for use with any type of laser, allowing an optimum selection for cost-effective material removal and balancing results.

Introduction

The MTI Model SS280 balancing system employs a pulsed laser that precisely removes material from parts as they rotate. The system uses pre-programmed microprocessors to acquire vibration data from existing sensors on a balance machine. This data, along with information stored in microprocessor memory, is used to determine the location and amount of material to be removed from each balancing plane. The laser is then directed to fire the number of pulses needed to remove the required amount of material from the rotating part. The system operates with closed-loop feedback using balance sensors from the machine to automatically update the laser commands. This assures that the residual imbalance is within operator-specified limits.

Laser balancing offers several advantages over the conventional approach of drilling or grinding away material[1]. The method does not rely on skilled operators to remove exact amounts of weight from locations that are often difficult to precisely identify and access. In addition, productivity is increased through the elimination of the time-consuming steps of removing parts from the balancing machine and regrinding and rebalancing until required tolerances are met.

The SS280 is readily adaptable to limited-access areas and offers simultaneous computation of all balance plane corrections, thus allowing complete balancing to occur with only one loading and spin-up cycle. Since the balance correction is performed by the laser under microprocessor supervision as the part rotates, human error and rejected workpieces are virtually eliminated.

The balance machine operator and SS280 microprocessor software interact through a video screen and key pad with multifunction switches. The operation needs no programming skills and responds only to system prompts when making control-related decisions. The MTI laser balancing system can be retrofitted to existing balancing machines, including low-speed balancing units, vacuum spin pits, and trim balancing systems. It can be used with any type of laser, allowing an optimum selection for cost-effective material removal and balancing results. The system is also capable of operating without a laser, while still taking advantage of the balancing software to compute balancing locations and weight corrections.

Various software packages are available that can be tailored to a customer's specific application. Uses range from multispeed, multiplane balancing of supercritical rotors to the retrofit of conventional, two-plane balance machines[2]. Potential uses include: production environments where large data bases exist and rapid throughputs are required; field services when access to machinery is limited and rapid solutions are required; and developmental programs where unique or prototype systems are encountered and vibrations must be kept to a minimum.

SS280 Microprocessor-Based System

System Overview

The SS280 microprocessor-based system, Figure 1, retains stored information for up to 10 different rotor types. A setup file contains parameters for each stored rotor type; these parameters include balance speed, allowable vibration limits, vibration specification, influence coefficients, and laser parameters, such as number of shots per index position, step size between indices, and maximum number of indices. The operator can change any of these values after entering the rotor type to be balanced, or the operator can enter a new rotor type and values for it.

The major balancing system components are:

- Balancing Processor - The balancing processor is an Intel 8085 microprocessor with the primary functions of execution of system software, communication to and from the display and laser control processors, and calculation of correction weights required for balancing.

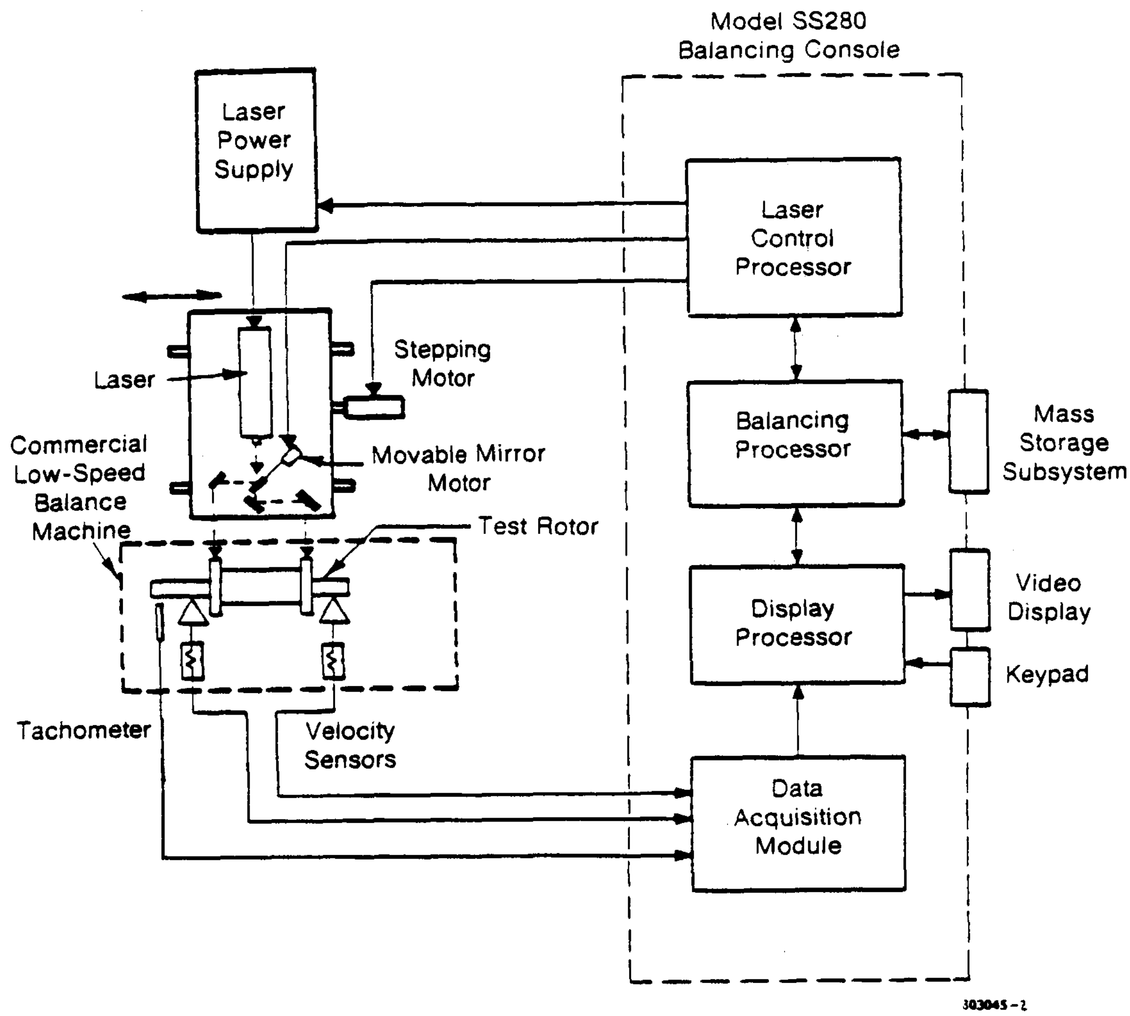


Fig. 1 MTI Microprocessor-Controlled Laser Balancing System Model SS280

• Display Processor - The display processor is an Intel 8085 microprocessor with the primary function of input/output from the system console. Operator instructions and data are displayed on the video screen, and the required operator input is communicated to the balancing processor.

• Video Display - A 9 in. screen with reverse video capabilities, in combination with the key pad and variable function switches, comprises the system/operator interface. The top two lines on the screen are reserved for error messages from the balancing processor and are always in reverse video. The screen pages change in response to the operator's responses.

• Key Pad and Variable-Function Switches - These are soft switches for numeric input by the operator. The five variable-funtion switches permit the operator to answer multiple-choice questions per the instructions on the screen. Also included are five fixed-function switches: YES, NO, STOP, DELETE and ENTER.

• Data Acquisition Module - The module consists of anti-alias filters, tachometer conditioning electronics, and an A/D converter. The anti-alias filters are used to bandwidth limit the vibration signals before the signals are digitized by the A/D converter. The tachometer conditioning electronics shapes the tachometer sensor signal in preparation for speed measurement. The data acquisition module is connected to and controlled by the display microprocessor.

• Laser Control Processor - The laser control processor is an Intel 8085 microprocessor with the primary function of firing the laser in the appropriate shot pattern. This includes limiting the burn zone to the balance plane dimensions, indexing of the laser after the required number of shots per index, balance plane selection and synchronization of the laser pulse to fire at the required angular location.

• Laser Subsystem - The subsystem includes the stepping motor, optics, and the laser. The stepping motor is used to step the laser beam axially across the balance plane. The optics include any mirrors required to access the required balance planes and a movable mirror that switches the laser beam from one balance plane to the other.

System Operation

The design of the SS280 laser balancing system emphasized simple operation that required no computer keyboard. The operator console, shown in Figure 2, contains the video screen, numerical key pad, five fixed-function switches, and five variable-function switches. From this console the operator can provide all the input required to run any of the following six programs:

- LBAL - Laser Balance Program - conducts automated laser balancing using either stored influence coefficient or trial weight methods
- MBAL - Manual Balance Program - provides operator with required correction weights for manual balancing without the laser
- PBAL - Production Balance Program - conducts automated laser balancing using stored data and requiring minimal operator inputs
- ICCALC - Influence Coefficient Calculation - calculates influence coefficients based on one or several trial weight balancing exercises for a given rotor type
- HELP - Help Function - assists operator in understanding use of other programs and in diagnosing errors
- TYPES - Creates New Rotor Type - allows introduction of a new rotor type for storage of balancing parameters.

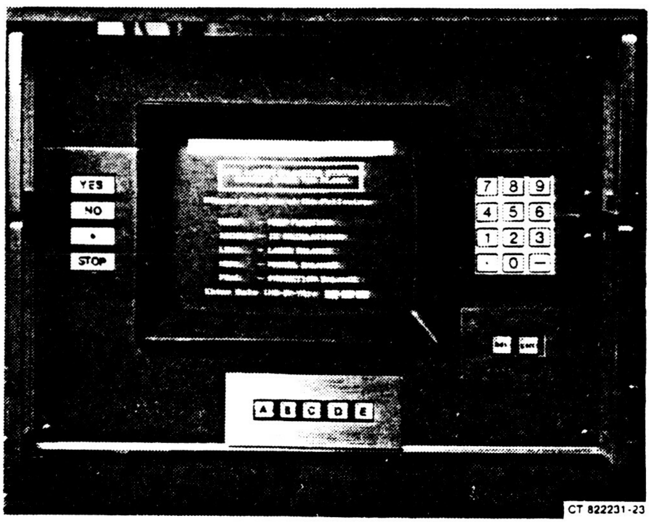


Fig. 2 MTI Model SS280 Operator Console

Balancing Methodology

The SS280 balancing software is configured to perform both trial weight and influence coefficient balancing of up to 10 different rotor types[3]. The present format is set up for single-speed, two-plane balancing, but it can be easily expanded to handle multiplane-multispeed applications. In addition to vibration sensors for each balance plane, the system requires a reference signal defining a zero position on the rotor. The zero position is used as a reference to time the firing of the laser pulse and to determine the proper angle for weight correction.

The SS280 system incorporates an MTI proprietary-design, phase-lock loop circuit and optic probe tachometer that allows the laser to repeatedly fire at the same angular position of a spinning rotor. This process is accomplished by using the optic probe and phase-lock circuit to determine the angular position of the rotating shaft while compensating for the laser firing time. The circuit is capable of responding in five-degree increments to a selected angular position and is referenced to an arbitrarily marked zero on the rotor.

As a first step in the balancing procedure, the initial rotor vibrations are recorded at a selected balancing speed. The results, which consist of amplitudes and phase angles (vectors), constitute the data for the uncorrected rotor. The laser is then programmed to fire multiple shots at a given angular location of the rotor in each balance plane. This procedure produces a change in the vibration at each sensor and is called trial weighting. By subtracting the corresponding results for the uncorrected rotor and dividing by the value of the trial weight removed from each balance plane, sensitivity data called an influence coefficient is obtained; one influence coefficient is obtained for each sensor at each balancing speed.

Since influence coefficient measurements have both amplitude and phase, they are treated as vectors. They define the resulting change in amplitude and phase angle at the sensors at a given speed and for a specified number of laser shots (material removal). Once all the influence coefficients are obtained for a certain rotor type, the laser shots required to minimize vibration of any similar rotor type placed in the balance machine may be computed. The computer then controls the laser system to remove the appropriate amount of material while the rotor is spinning. Weight removal is carried out automatically with closed-loop feedback to insure the laser removes only enough material required to effectively balance the rotor. Levels of residual imbalance are specified by the operator and may be as low as the sensitivity level of the vibration sensors. The influence coefficient balancing approach is useful for balancing both rigid and flexible rotors.

Laser Machining

Laser machining is basically a high-speed process in which the ablation of a very small portion of material takes place so rapidly under the high intensities of a focused laser beam that substantial force is transmitted to the adjacent liquid material formed on the surface of the part by laser heating. Thus, material leaves the surface not only through ablation, but also in the liquid state at a relatively high velocity.

A laser system, for example, with an output of 40 joules and a pulse duration of 1 millisecond has a corresponding peak power of 40,000 watts. A typical beam divergence of this system is less than 15 milliradians. If a focus lens of 4 inches is used to focus the energy, the spot area exposed to the focusing laser beam becomes 0.49 x 10E-3. square inch. Thus, this focused beam results in a power density of 81 x 10E2 watts/square inch, an amount sufficient to vaporize any known material.

The amount of energy needed to raise a volume of material to its vaporization point can be approximately calculated as the energy required to raise the metal to its vaporization point plus the latent heat of fusion and vaporization. The energy required to vaporize 1.0 gram of metal can be calculated in the following steps:

1. Heating from room temperature to melting point:
$$E_1 = C(T_m - T_o) = 0.11\ (1535 - 20)$$
$$= 167 \text{ calories}$$

2. Changing from solid to liquid at T_m:
$$E_2 = L_f = 65 \text{ calories}$$

3. Heating from melting point to boiling point:
$$E_3 = C(T_b - T_m) = 0.11\ (3000 - 1535)$$
$$= 161 \text{ calories}$$

4. Changing from liquid to vapor at T_b:
$$E_4 = L_v = 1630 \text{ calories}$$

Thus,
$$E_1 + E_2 + E_3 + E_4 = 2023 \text{ calories}$$
$$= 8500 \text{ joules/gram}$$

where:
- C = specific heat in cal/g
- T_o = ambient temperature in °C
- T_m = melting temperature in °C
- T_b = boiling temperature in °C
- L_f = heat of fusion in cal/g
- L_v = heat of vaporization in cal/g.

The removal rates can then be calculated for a single pulse of a 40-joule laser as 5 milligrams removed.

MTI's experience has shown that the material removal rate decreases with increasing rotor speed as characterized by the graph in Figure 3. This graph is based on firing laser shots with a 40-joule Nd:glass laser having a maximum repetition rate of one shot every 2 seconds.

Currently, lasers of the neodymium:yttrium aluminum garnet (Nd:YAG) variety are available with considerably higher power and faster firing rates than the Nd:glass laser. The Nd:YAG lasers are capable of removing material more rapidly. The advantages of Nd:YAG over other solid-state laser materials as a laser balancing tool are numerous. These include:

- Operation is normally without cryogenic cooling of the crystal.
- The Nd:YAG laser can routinely be operated at high average powers and high energy per

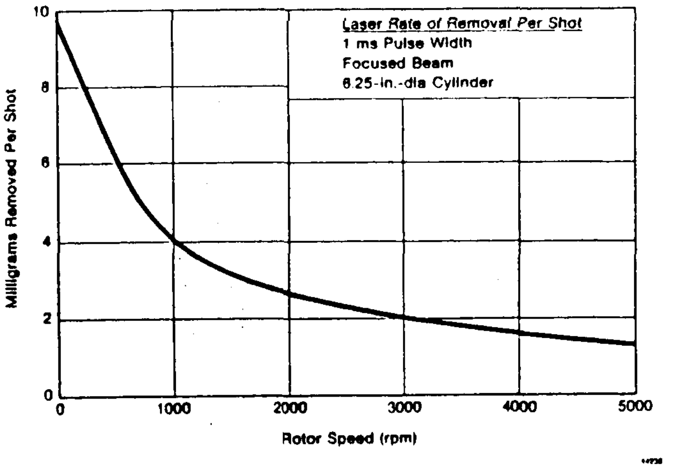


Fig. 3 Rate of Removal Per Shot versus Rotor Speed

pulse without damage. Industrial equipment that delivers up to 500 watts average power from a single rod and up to 1000 watts average power from multiple rods is available.

- Nd:YAG lasers are generally quite compact in comparison to gas lasers of equivalent power. The laser head of a typical 400-watt unit will measure less than 1 meter in length, including beam handling optics.
- The output wavelength at 1.06 µ allows use of conventional transmission optics made of fused silica or other glass.
- The relatively good absorption characteristics exhibited by most metals at 1.06 µ negates the necessity to use special absorptive coatings. The effect of wavelength is especially worth noting with regard to processing of high reflectivity metals such as aluminum, copper, and their alloys.

MTI internal studies show that with a 400 watt Nd:YAG laser the material removal rates are 15 times faster than previously achieved with Nd:glass lasers. One such test produced a removal rate of 70 mg/s from a turbine steel rotor at a surface speed of 2.7 m/s and a pulse rate of 10 shots/s. These experiments indicate that lasers recently introduced for commercial use will be able to handle removal rates necessary for laser balancing gas turbine sized rotors in a reasonable amount of time without requiring additional hardware or material coatings to enhance removal capability.

A more powerful laser functioning at a much faster firing rate will impart significantly more energy into the rotor during the laser machining process. This energy, in turn, will tend to promote a larger heat-affected zone surrounding the laser burn, and could possibly lead to a reduction in fatigue life of laser fired materials.

Process Optimization

Many parameters in the laser machining process affect the rate of material removal and, consequently, the fatigue strength of the laser-fired material. The key parameters are as follows:

- Material
  - Microstructure
  - Melting Point
  - Surface Finish
  - Reflectivity

- Laser
  - Wavelength
  - Power
  - Pulse Width and Rate
  - Beam Diameter

- Machining System
  - Surface Speed
  - Focus
  - Focal Length
  - Laser Shots Fired per Index
  - Index Step Size and Rate
  - Number of Passes Across Laser Burn Zone

Basically, a trade-off exists between the maximum material removal rate desired and the extent of the laser affected zone (LAZ) and its resultant reduction in fatigue strength. By careful adjustment of the parameters, the trade-off can be optimized to minimize the penalty of reduced fatigue strength while obtaining reasonably high material removal rates.

Practical constraints relating to balancing requirements for a given rotor must also be considered when selecting key parameters. For example, if the laser arc length is excessively large, the weight correction provided by laser machining will not be sufficiently concentrated to provide a meaningful balance correction. Also, energy input into the material must be sufficiently high to vaporize the material completely, otherwise the surface layer will resolidify and remain attached to the rotor. This formation of slag within the laser burn zone must be avoided since it effectively lowers the actual removal rate. A method has been developed to ensure that resolidification does not occur.

Conclusions

In summary, MTI has developed a programmable laser balancing system capable of automatically balancing rotors at speed. The implications of replacing the conventional balancing method with its hand grinding of material has been considered from the viewpoint of possible fatigue life reduction. Although initial experiments have shown that fatigue life reduction due to the laser is no worse than due to hand grinding for most materials, further work is necessary to verify this conclusion. The key parameters that effect the rate of laser material removal and the quality of laser burn zone surface finish have been identified. Work continues on optimizing these parameters for a variety of different applications concerning new materials, component configurations, and laser systems.

References

1. Tessarik, J. M., and Fleming, D. P., "Tests of Laser Metal Removal for Future Flexible Rotor Balancing of Engines", SAE Paper 750170, Presented at the Automotive Engineering Congress and Exposition, February 1975.
2. DeMuth, R. S., Fleming, D. P., Rio, R. A., "Laser Balancing Demonstration on a High-Speed Flexible Rotor", ASME Paper 79-GT-56, Presented at the Gas Turbine Conference and Exhibit, December 1979.
3. Martin, M. R., "Model SS280 Microprocessor Laser Balancing System", MTI Report 83TR65, Prepared under MTI IR&D Contract 0238-23602, September 1983.

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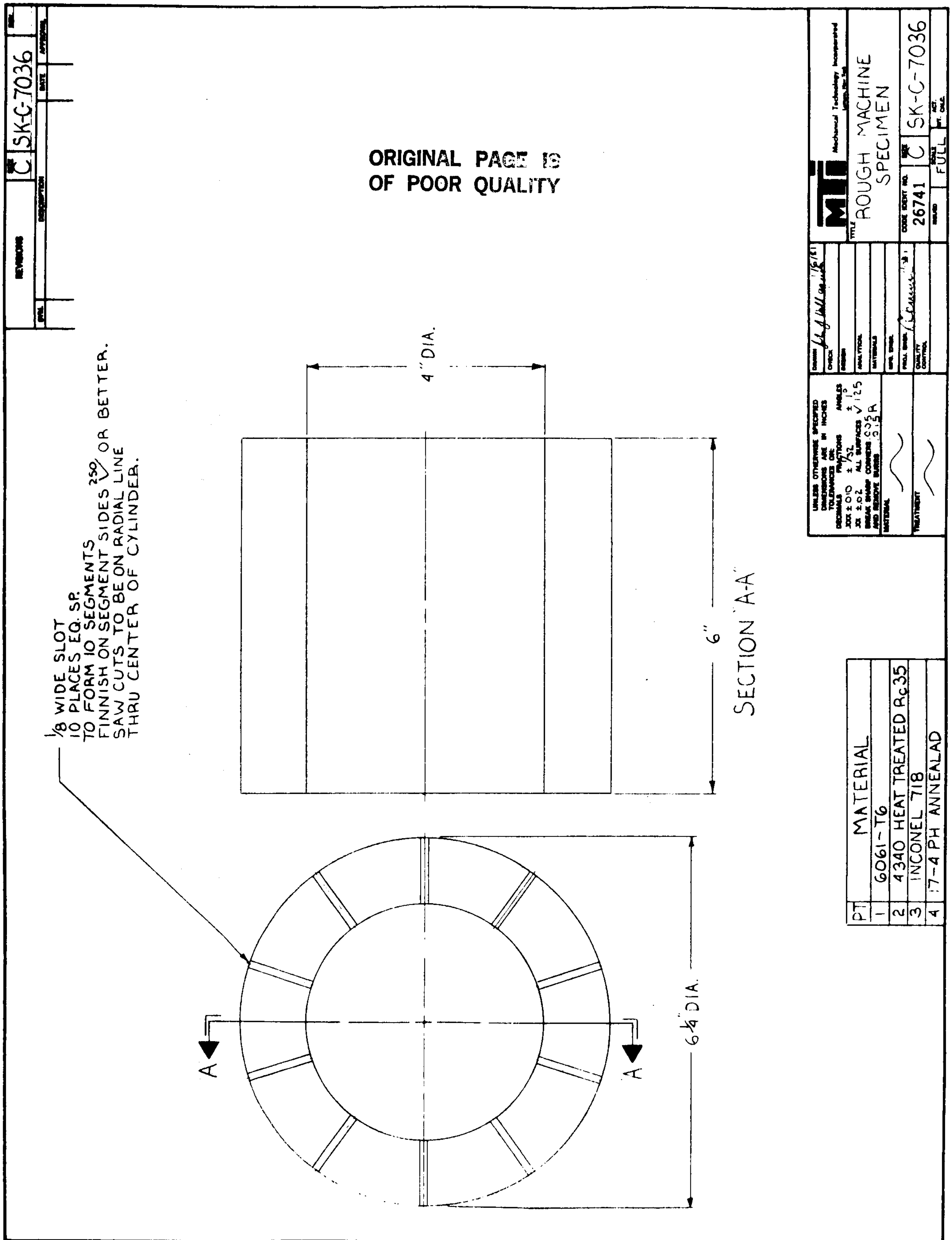
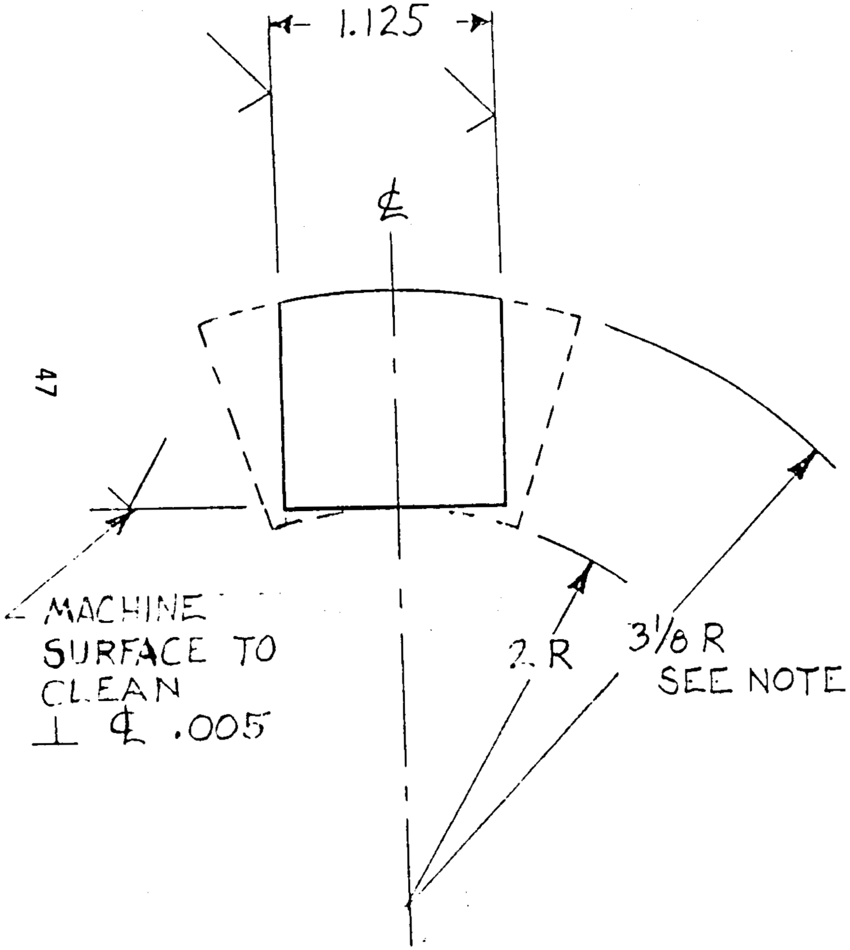
APPENDIX B

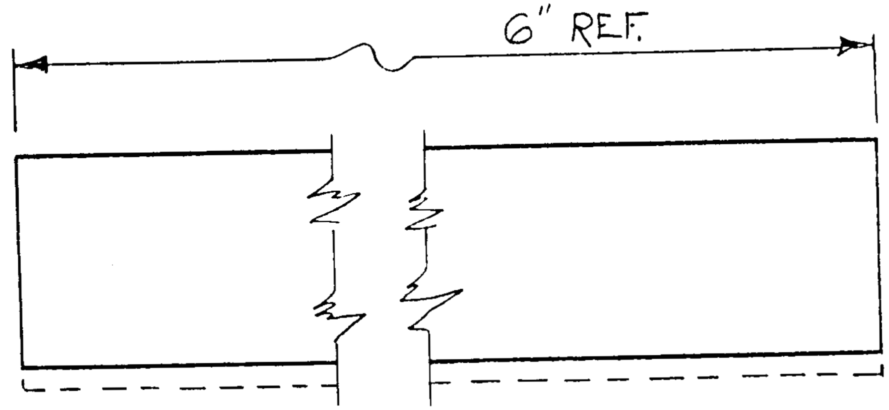
Fatigue Specimen Data


REVISIONS
C SK-C-7036
1/8 WIDE SLOT
10 PLACES EQ. SP.
TO FORM 10 SEGMENTS
FINNISH ON SEGMENT SIDES 250 OR BETTER.
SAW CUTS TO BE ON RADIAL LINE
THRU CENTER OF CYLINDER.
4" DIA.
6"
SECTION A-A
6 1/4" DIA.
A
A
PT | MATERIAL
1 | 6061-T6
2 | 4340 HEAT TREATED Rc 35
3 | INCONEL 718
4 | 17-4 PH ANNEALAD
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
MATERIAL
TREATMENT
Mechanical Technology Incorporated
ROUGH MACHINE SPECIMEN
CODE IDENT NO. 26741
SIZE C
SK-C-7036
SCALE FULL

NOTES:

1. 3⅛ RADIUS NOT TO BE MACHINED
2. 32 OR BETTER ON SURFACES INDICATED
3. DASHED LINES INDICATE MATERIAL TO BE REMOVED





LASER BURN TEST SPECIMEN	
SCALE - FULL	DATE - 5-23-84
PROJ Nº 0530 44682	DRAWN - P. QUANTOCK
DRAWING Nº SK-C-7036-A	

APPENDIX C

Material Certification

MO0295 1 NP

AREA CODE 312
587-1000

PLANTS:
CICERO, IL.
CLINTON, WI.
SPRING GROVE, IL.

SCOT FORGE

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ORDER NO.

03984

BOX 8
SPRING GROVE, IL 60081

MATERIAL CERTIFICATION

MECHANICAL TECHNOLOGY INC
968 ALBANY-SHAKER ROAD
LATHAM NY
121.0

CUSTOMER ORDER NUMBER	ITEM	OF	CUSTOMER JOB NUMBER	DATE SHIPPED
405-02685	2	2		05 13 84

PART NUMBER	B/P NUMBER	VIA	DATE PREPARED
		PRESTON	05 04 84

DESCRIPTION OF MATERIAL AND SPECIFICATIONS

RING
STEEL TO MEET MIL-S-5000
(AISI 4340 A Q)
QUENCH & TEMPER TO 331/375 BHN
6-1/4" O.D. X 4" I.D. X 6" FACE
ALLOW FINISH ALL OVER

NO. OF PIECES 1 HEAT NUMBER 5V-1538 (MILL - STANDARD STEEL)

C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Al	V	Grain
41	.68	.013	.01	.25	1.83	.79	.24	.12			6

* JOMINY HARDENABILITY *

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	18	20	24	28	32
					55												55			

HARDNESS RESULTS

PCS	BRINELL 3000 KG LOAD
1	341

FREQUENCY = .000 SEVERITY = .000
MACRO ETCH INSPECTED AND RESULTS ACCEPTABLE

THIS IS TO CERTIFY THAT THE REPORTED LADLE ANALYSIS (AND/OR TESTS) SHOWN ON THIS REPORT ARE CORRECT AS CONTAINED IN THE RECORDS OF THE COMPANY.

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BY: ____________

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Clinton, WI
Spring Grove, IL

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754283 SCOT UD

8001 Winn Road
Box 8 Spring Grove, IL 60081
312/587-1000

TOLL FREE 800-435-6621
(OUTSIDE OF ILLINOIS)

ORDER NO

MECHANICAL TECHNOLOGY, INC
968 ALBANY-SHAKER ROAD
LATHAM, NY
12110

MATERIAL CERTIFICATION

CUSTOMER ORDER NUMBER	ITEM	OF	CUSTOMER JOB NUMBER	DATE SHIPPED
405-02681	1	2		06/20/94

PART NUMBER	B/P NUMBER	VIA	DATE PREPARED
		UPS	[illegible]

DESCRIPTION OF MATERIAL AND SPECIFICATIONS

RINGS
TYPE 17-4 PH STAINLESS STEEL
(CHEMISTRY PER AMS 5643)
SOLUTION TREAT @ 1900 DEGREES F FOR 1/2 HOUR - AIR COOL
AGE @ 1025 DEGREES F FOR 4 HOURS - AIR COOL (352/375 BHN)
6-1/4" O.D. X 4" I.D. X 6" FACE
TOLERANCE : PLUS OR MINUS 1/32" ON O.D.
PLUS OR MINUS 1/16" ON I.D.
PLUS 1/8" MINUS 0" ON FACE
ROUGH MACHINE TO SIZES SHOWN - 125 RMS

NO. OF PIECES 1 HEAT NUMBER 85591 (MILL - ANDERSON-SCHUMAKER)

C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Al	V	GRAIN
.04	.74	.03	.003	.44	4.67	15.68	.37	3.51			

Cb	Co	Ta
.25	.07	.01

HARDNESS RESULTS

PCS	BRINELL 3000 KG LOAD
1	352/363 OK

OK

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21787

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334 West 8th South, Salt Lake City, Utah 84101, TELEX 38-8330, Phone 801-322-3533
2715-6th Avenue South, Seattle, Wash. 98134, TELEX 32-9463, Phone 206-622-6086

MECHANICAL TECHNOLOGY INC.
P.O. Box 805
Latham, New York 12110
ATTN: PURCHASING DEPARTMENT

CUSTOMER ACCT. NO.	
791061	
INV. REQ'D.	SPEC. CLAUSES
3	
TAXABLE	NON-TAXABLE
	X
CALL	OUR TRUCK
PREPAY	COLLECT
	X
VIA	
T	
DATE SHIPPED	
PARTIAL	COMPLETE

CUSTOMER'S ORDER NO.	ORDER DATE
405-02680	29MAR'84

SAME
968 Albany - Shaker Road
Latham, New York 12110

ITEM NO.	QUANTITY ORD	QUANTITY SHIP	DESCRIPTION
51			Forged Aluminum Alloy, Type 6061-T6 with Chemistry, BHN and Heat Treatment; In accordance with ASTM-B-247-82. ALL MECHANICALS WAIVED.
01	1		PC. OVERSIZED TO FINISH: 6-1/4"OD, 4"ID, 6"LG.
	3		PCS. R/M: 6-1/4"OD, ~~4"ID~~, 6"Long
			(TOLERANCE: +,-1/32"(OD); +,-1/16"(ID); +1/8",-0(LG))

MARKING AND PACKAGING REQUIREMENTS
CSF STD
STEEL STAMP "6061-T6" ON EACH PIECE

METALLURGICAL REPORT REQUIREMENTS		
NOTARIZE	W/SHIPMENT	W/B LADING
	2	1

MAIL 1 — COPIES TO:
GREG MIGIRDITCH

METALLURGICAL REPORT
ALUMINUM AND ITS ALLOYS

Item No.	Heat No. or Indent.	Cu.	Fe.	Si.	Mn.	Mg.	Zn.	Ni.	Cr.	Ti.
	46125	.25	.30	.72	.06	1.01	.05		.10	.03
	JIXS							OET <.15	Al Rem	

Item No.	Hardness of Material Supplied	Tensile	Yield —% Offset	El.	R.A.	BHN.	Size of Raw Stock	Mill
	BHN 109						5-3/4"	KAISER

Heat Treatment: 1) Solution heat treated at 985+10°F. for 6 hours and water quenched in 80°F. to 100°F. water; and 2) Aged at 355+10°F. for 10 hours and air cooled

Acceptable
[illegible signature]
4-2-84

We certify that the material described herein has been inspected and/or tested for conformance to the applicable specifications. Our warranty of quality provides for replacement only of any part of this material which subsequent inspection, test or use shows non-conformance with the specification. Inspection records, certifications, chemical and/or physical test reports are on file for your examination at EMERYVILLE, CALIFORNIA.

COULTER STEEL & FORGE COMPANY

By [signature]

Title QUALITY CONTROL MANAGER

ORIGINAL PAGE IS
OF POOR QUALITY

ORIGINAL PAGE IS OF POOR QUALITY

SCHLOSSER FORGE COMPANY

11711 ARROW ROUTE CUCAMONGA, CALIFORNIA 91730

METALLURGICAL ANALYSIS REPORT

CONDITION OF FORGINGS

Solution Treat @ 1925°F - 1 hr. - fan cool, Age @ 1400°F - 10 hrs. - furnace cool 100F/hour to 1200°F - 8 hrs. - air cool @ Aerocraft Heat Treating Company. Rough Machined.

FORGINGS FLUORESCENT PENETRANT INSPECTED PER:

FORGINGS ULTRASONIC INSPECTED PER:

MECHANICAL PROPERTY ACCEPTANCE OF LISTED FORGINGS ARE BASED ON RESULTS FROM: [X] SECTIONED FORGINGS OR ROLLED RING [ ] INTEGRAL TEST RING OR SLUG [ ] SEPARATELY FORGED TEST BAR

PER: [ ] LOT [X] HEAT [ ] FORGING

DATA SOURCE [X] S F C [ ] MILL

DELIVERY MEMO No. 27040 — REFER TO THIS NO. IN ALL CALLS AND CORRESPONDENCE

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4-0431	405-02679	Consolidated Freightways	6/19/84	6/19/84			3 + T.F.

MATERIAL	PART NO. OR DESCRIPTION	SPECIFICATIONS
Inco 718	6.250 x 4.000 x 6.000	AMS 5664B

IDENTIFICATION			CHEMICAL ANALYSIS													
MILL	HEAT NO.	CODE	C	MN	P X	S X	SI X	CR	MO XX	NI	AI	TI	CU X	FE	CB/TA	CO X	XX B
Special Metals	99046		.036	.11	*.010	.004	.14	18.2	3.04	53.3	.50	.94	*.10	17.9	5.23	.43	.003

*Denotes Less Than

SERIAL	CODE	TENSILE: TEST LOCATION & DIRECTION	TEMP °F	YIELD 2% OFF. KSI	ULTIMATE KSI	% ELONG. IN 4 D	% RED OF AREA	S R	STRESS RUPTURE: STRESS KSI	TEMP. °F	HRS. TO BREAK	% ELONG IN 4 D	INCREASE STRESS TO	BHN
														415

REMARKS:

CODE	CLEANLINESS AMS FREQ. SEV.	JOMINY HARDENABILITY ROCKWELL "C" SCALE IN 1/16"

COPIES OF ACTUAL TEST REPORT SHOWING CONFORMANCE TO APPLICABLE SPECIFICATIONS ARE ON FILE AT OUR PLANT AND ARE AVAILABLE FOR REVIEW BY YOU OR YOUR COGNIZANT REPRESENTATIVE — WE HEREBY CERTIFY THESE FORGINGS HAVE BEEN TESTED, INSPECTED AND ACCEPTED IN ACCORDANCE WITH THE APPLICABLE BLUE PRINTS AND SPECIFICATIONS.

I CERTIFY THAT TO THE BEST OF MY KNOWLEDGE AND BELIEF THIS MATERIAL ANALYSIS REPORT IS TRUE AND CORRECT

David Robinson

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15. Supplementary Notes

Project Manager, David P. Fleming, Structures Division, NASA Lewis Research Center.

16. Abstract

Fatigue tests were conducted to determine the actual reduction in fatigue life due to weight removal for balancing by: hand grinding, low power (20 watt) Nd:glass laser and a high power (400 watt) Nd:YAG laser.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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